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GEOPHYSICAL PROSPECTING FOR UNDERGROUND WATERS IN DESERT AREAS

BY

F. W. LEE

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GEOPHYSICAL PROSPECTING FOR UNDERGROUND WATERS IN DESERT AREAS[1/]

By F. W. Lee[2/]

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INTRODUCTION

The paramount importance of water to life of all forms on the earth is too well known to require elaboration in this brief paper. It has repeatedly been termed the most valuable of all our mineral resources. Its importance is justifiably recognized in the extensive areas covering the earth which receive sufficient rainfall to sustain a relatively luxuriant vegetation; but in those areas where rainfall is insufficient to support anything but a relatively meager plant growth, the location of a water supply and its development become of even more vital interest to those attempting to obtain a living from the soil.

Geological investigations concerning the water supply of the United States have been most extensive, important work having been accomplished by Federal, State, and local governments and by private enterprise. A casual examination of the titles of the 739 Water-Supply Papers published by the United States Geological Survey[1/] alone testifies to the vital nature of our water resources and the extensive work that has been done on them.

In relatively recent years the science of geophysics has developed into a most important tool to supplement geology in mineral exploration work, and there is probably no branch of geophysics that is of more common interest than that touching hydrology, especially the knowledge of ground water and its relation to the geology of water-bearing structures.

Even today, largely due to this universal interest in underground water and the lack of knowledge by the layman concerning such matters, there are many popular misconceptions concerning subterranean water. It is commonly believed that water generally flows underground in very much the same manner as it does on the surface, except that the channels are subterranean. Moreover, it is a popular fancy that some persons are able to locate such channels with the aid of willow, hazel, peach and other forked branches. (See appendix on divining rod.)

Other erroneous ideas that bear directly upon the application of modern geophysical methods of prospecting are that the supposed water courses or channels are good conductors of electricity and should therefore act very much as similarly shaped isolated conductors of electricity in the earth. Because some electrical conductors behave in a very characteristic manner that permits them to be found, it may be thought that it should be a simple matter to identify such subsurface bodies of water in much the same way, especially since it is often possible, by means of these properties, to prospect geophysically for ore bodies in a very successful manner. At present, however, there is no geophysical method for differentiating underground water from other buried electrically conducting bodies.

The purpose of this paper is to describe methods and results of geophysical prospecting for water in Nevada and adjacent States. There are included discussions of some of the associated problems relating to field technique and geologic interpretations, and some of the problems a field engineer encounters, the solution of which often contributes to the success or failure of his work.

1/ U. S. Department of the Interior, Publications of the United States Geological Survey; August 1934, pp. 98-142.

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FUNDAMENTAL PHYSICAL RELATIONS PERTAINING TO GEOPHYSICAL PROSPECTING FOR WATER

A knowledge of fundamental principles of occurrence of ground water is, of course, essential to intelligent geophysical prospecting for it. Such information may be found in numerous books and papers on geology, physiography, hydrology, etc. Outstanding among these is the work of Meinzer[1].

Small amounts of water usually are present in the soil at depths of only a few inches. Even the surface soil contains a certain percentage of moisture tightly held either by molecular attraction between the soil particles and the water (adhesion) or chemically held, which can only be removed by heating or by chemical reaction. These small quantities, however, produce measurable physical effects. This water present in the surface soil is discharged into the atmosphere in perceptible quantities by the action of plants or by soil evaporation, and is termed "soil water." Next below the "soil water" is an intermediate zone, in which water is either drawn downward by gravity to the underlying zone of saturation or held nearly stationary by molecular attraction. Eventually, the interstitial openings present in the ground become thoroughly saturated with water, constituting the zone of saturation. The upper surface of this zone is known as the "water table," which is not a plane surface but generally tends to conform somewhat with the topography. Immediately above the water table is a zone termed the "capillary fringe," in which some or all of the capillary openings in the ground are filled with water drawn from the zone or saturation.

Because of this universal presence of water in the ground, geophysical methods for locating water per se cannot be applied successfully. However, underground water generally occurs in small interstices in other earth materials, and it is the writer's opinion that such water has a very marked influence on the electrical resistivity of the various earth constituents in which it occurs. For this reason it is generally meaningless to measure the resistivity of rocks and other earth materials without including studies on the effect of varying amounts of water in them; the best place for measurement, of course, is where they are actually in situ. Moreover, since water changes the resistivity of various beds by different degrees, in many instances it is possible to differentiate such beds, using electrical methods depending on resistivity and polarization.

Another important factor that bears directly upon the water question is the rate of water seepage through loose superficial deposits. Observations in the Humboldt River Valley and recorded in this report show the influence of this factor. Here many stream courses drain into the main valley. Thus, a given volume of drainage ground, especially porous gravel beds, is alternately emptied by migration and evaporation and filled by rainfall or melting snows. The clay beds that generally seal desert water bodies permit water to circulate through them only at exceedingly slow rates, even though they may contain high percentages of water held molecularly in capillary and subcapillary openings. The

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[1] Meinzer, O. E., The Occurrence of Ground Water in the United States, with a Discussion of Principles: U.S.Geol. Survey Water-Supply Paper 489, 1923, 321 pp. Outline of Ground-Water Hydrology, with Definitions: U.S. Geol. Survey Water-Supply Paper 494, 1923, 71 pp.

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mineral salts commonly found in clay deposits greatly reduce their electrical resistivity, however. Thus, the normal effect of water in gravel is to increase its electrical resistivity, while in the adjacent material it may decrease it. For this reason it may be stated that, in general, impervious alluvium is a better conductor than the more porous gravel formations. Many observations were made on these several kinds of materials.

It is also a fact that water will gravitate, unless checked by surface tension, until it encounters a relatively impervious layer, such as through opening in limestone to underlying shale or through sandstone downward to granite. Such cases call for differentiation of the contact zones and making a structural contour map of the contacts as a guide for determining the best locations for finding water. It is generally true that the electrical resistivity of granite is greater than that of sandstone and that of limestone higher than that of shale. Hence, geophysical prospecting for water becomes more complex with increase in the variety of rocks, with each district constituting a separate problem.

ELECTRIC CONDUCTION IN THE GROUND

Many writers assume that the electric current always passes through the ground with what may be called ohmic conductivity, in very much the same manner as current flows through a metallic conductor. Under this supposition the ground has various degrees of ohmic conductivity, differing in value and in direction under a given set of geologic conditions. Actual observations show that other factors often are controlling. It appears that a system of electrolytic cells is gradually built up in the ground that opposes the passage of an electric current through it. In such a system there would be a chain of cells from one zone of influence in the near vicinity of the ground current stakes that would be electrically weaker than the adjacent chains. The weak chains will break down first and thus confine the path of the current to definite channels instead of distributing it uniformly through the whole medium according to ohmic conductivity. In other words, the flow of current would be similar to that through a broken artificial electrical insulation, except that in the soil the voltage gradient is of the order of microvolts per centimeter, while in artificial insulation it is of the order of hundreds of kilovolts per centimeter. In support of this theory, oscillographic records of the current in dielectrics and in the ground are strikingly similar in character. Also, it is often possible to observe the gradual building up of the resisting cells in the change of current that accompanies resistivity measurements. A ground characteristic of this kind may account for the fact that at some electrode spacings a great difference of apparent electrical resistivity is observed. This question is not definitely settled, nor have its many phases been examined experimentally.

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PHYSICAL FEATURES OF TYPICAL NEVADA DESERT VALLEY PERTAINING TO WATER SUPPLY

Since it is very important that the reader obtain a clear-cut idea of the physical features pertaining to water supply that obtain in a typical desert valley underlain by water-bearing fill, the following description, taken from Meinzer[5], is presented.

Big Smoky Valley is a typical Nevada desert valley - a plain hemmed in by mountain ranges and underlain by porous rock waste eroded from these ranges and saturated with water discharged from them. Like most of the valleys of the State, it has a general north-south elongation and an interior drainage. A low, gentle, alluvial swell divides the area draining to Big Smoky Valley into a north basin, which contains the upper valley and a south basin, which contains the lower valley. Each of these basins held a lake in the Pleistocene epoch and now contains an alkali flat.

The north basin has an area of about 1,250 square miles. Like most other desert basins, it comprises two strongly contrasted types of topography, one in the mountains and the other in the valley. The mountains have a relief of several thousand feet, and their surface has been eroded or carved by streams; the valley has a relief of only a few hundred feet, and most of its surface is formed of deposits laid down by streams. The mountains are steep sided and almost infinitely varied in topographic detail; the valley consists of smooth, gentle slopes and nearly level plains. In general, the relation of the mountains to the valley is that of cause and effect, and a study of the physiography of the basin, therefore, consists largely in correlating the land forms in the valley with the causal conditions in the mountains.

The greater part of the valley surface consists of coalescing alluvial fans or slopes built of the rock waste discharged from the canyons. At their bases the slopes become very gentle and merge, in many places imperceptibly, into large playas, or alkali flats, that occupy the lowest parts of the valley. Superimposed on these main features are numerous scarps produced by recent faulting, large ridges built by ancient lakes, hills and ridges of sand heaped up by the wind, and in a few places mounds and terraces built by springs. The alluvial fans have also been modified by large, deep streamways carved into them.

The valley is nearly surrounded by a mountain wall, in which are cut innumerable notches of various sizes. Each notch is the mouth of a canyon - the portal through which a certain part of the mountain area makes its contributions to the valley, not only of the water that falls upon it as rain or snow but of the very substance of the mountains themselves. The water that is discharged at the surface or as underflow is the vehicle by means of which the transportation of this rock material is effected, the soluble matter being carried in solution, the fine particles of sand and clay held in suspension, and the pebbles and boulders rolled over the surface by the impact of the water. Only from the larger canyons are these contributions made continuously, most of the canyons being dormant the greater part of the time and becoming active contributors only at long intervals when freshets occur. The character and quantity of the contributions that the valley receives through these notches

5/ Meinzer, O.E., Occurrence of Ground Water in the United States: U.S. Geol.Survey Water-Supply Paper 489, 1923, pp. 298-303. (Mainly quoted from Meinzer, O.E., Geology and Water Resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada: U.S. Geol.Survey Water-Supply Paper 423, 1917, 167 pp.

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determine almost exclusively the shape of its surface, the distribution and capacity of its water-bearing beds, the quantity, quality, and level of its ground water, the character of its soil and native vegetation, and the agricultural possibilities of its lands.

At the mouth of each canyon is an alluvial fan built of the materials contributed by the canyon. Each of these fans is or has been the greatly expanded streamway or flood plain of the stream that periodically flows from the canyon. The floor of a canyon and the surface of an undissected fan form parts of a single stream profile and are as closely adjusted to each other by the laws of stream gradation as the upper and lower courses of more ordinary streams. All the fans have the same general form because they are produced under the same general conditions. Each has an apex at the mouth of the canyon, from which it extends downward in all directions except as it is limited by other land forms. In each the grade diminishes with distance from the apex, thus giving the fan a concave profile along a line drawn from the apex in any direction in which the fan extends. In their size and in the shape of their concave profiles, however, the fans differ as widely as the canyons from which they are supplied. These differences are never haphazard but are determined by the sizes and gradients of the canyons, the volume and character of the floods which they discharge, and the quantity and nature of rock waste which the floods have to handle.

As the canyons are not far apart, their fans are crowded together and modified by each other. Many small fans are superimposed on the larger ones, and fans of nearly equal size merge with each other in their middle and lower parts, forming a single smooth slope, a given point of which may receive sediments from two or more canyons.

As in most localities, the contributing mountain areas on opposite sides of the valley differ in size, corresponding fans are likewise unequal, and the axis or line of lowest depression is not in the middle of the valley but relatively far from the side on which the mountains are large and near the side on which the mountains are small. The largest mountains are not, however, all on the same side, but are here on one side and there on the other. Consequently, the line of lowest depression is a sinuous line that keeps far away from the large mountains.

The north basin once contained a lake whose surface fluctuated but never rose high enough to have an outlet. When at its highest level it was about 40 miles long, 9 miles in maximum width, and covered an area of approximately 225 square miles, or 18 per cent of the drainage basin in which it lay. Its maximum depth was about 170 feet. The shore features consisted almost entirely of gravelly beaches and beach ridges or embankments, many of which are very definite structures that can be followed for a number of miles, the largest attaining heights of nearly 50 feet.

At present the valley contains no perennial lake, but the flood waters that are not lost in their descent over the fans are impounded in the lowest parts of the valley, from which they are removed almost exclusively by evaporation. The impounded waters are always roily and on evaporation deposit fine sediments. This process of aggradation is as characteristic of the desert

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valleys as the aggradation on alluvial fans through deposition by running waters, and it produces as distinct a type of land surface. The running waters form surfaces with grades, whereas the impounded waters form surfaces that approximate horizontal planes.

The valley is arid. At one station the precipitation in 6 years averaged only 6.55 inches a year and in no year amounted to as much as 9 inches. In the higher mountains the precipitation is appreciably greater. About 50 of the canyons that drain into the upper valley contain small perennial streams.

The bedrocks of the drainage basin are relatively impervious and form a huge reservoir that is nearly water-tight. In this reservoir rests the great accumulation of porous rock waste called the valley fill, which is saturated with water up to a certain level known as the water table. The great body of water that is stored underground in this natural reservoir is derived from the rain and snow that fall upon the drainage basin. Contributions to the water in the valley fill are made by the perennial streams that flow out of the larger canyons, the floods discharged at long intervals from the canyons, which are normally dry, the underflow of some of the canyons, the rain that falls in the valley, and water discharged underground from openings in the bedrocks.

It is roughly estimated that the perennial streams together contribute to the underground supply at an average rate of 15,000 to 30,000 acre-feet a year, most of which goes to the upper valley. The total annual recharge is considerably greater.

The contributions of water to the underground reservoir are balanced by losses from this reservoir. The losses occur chiefly through the return of the ground water to the surface but in smaller part through percolation out of the basin by way of underground passages. The return water reaches the surface by flowing from springs or by rising through the capillary pores of the soil or the roots and stems of plants where the water table is near the surface; it is all eventually evaporated. Ground water is returned to the surface over an area of about 160 square miles, or 100,000 acres, in the upper valley. The main west-side spring line extends, with a sinuous course due to differences in the sizes of alluvial fans, a distance of more than 30 miles and includes innumerable springs that discharge a part of the copious underground supply received from the Toyable Range. On the east side there is no spring line comparable to that on the west side, probably because the supply from the relatively low range on the east side is smaller than that from the higher mountains on the west. On the alluvial slope between the main west-side spring line and the mountains a few springs, which flow from fault scarps, are apparently produced by impounding caused by dislocation of the valley fill. The data seem to indicate that the quantity of water discharged from the main body of ground water in the upper valley is between 50,000 and 100,000 acre-feet a year, or between about 8 and 17 percent of the precipitation on the north basin.

In the upper valley, an area of about 100,000 acres has a depth of less than 10 feet to the water table, an area of about 170,000 acres has a depth of less than 50 feet, and an area of about 215,000 acres has a depth of less than 100 feet.

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The coarse clean sand or grit derived from granite is porous and yields water freely. The arkosic grit derived from rhyolite and other igneous rocks of fine grain also generally yields water freely, but it contains more fine material and when it disintegrates it becomes quite compact. The pebbles derived from the angular fragments resulting from the weathering of slate and limestone may produce porous deposits, but the pores are likely to be sealed to some extent by the cementation of calcium carbonate. The sediments derived from the tuffs are largely fine silt and form dense deposits that will yield little water. In the upper valley there are no wells that have been pumped at a rate of more than a few gallons a minute, but the evidence furnished by the character of the rocks in the adjacent mountains and the character of the sediments as shown at the surface and in well sections indicates that in most places between the 100-foot line and the flat wells yielding moderately large supplies can be obtained. A well in the lower valley is pumped at the rate of 400 gallons a minute.

Several flowing wells have been sunk in the valley. These wells are all in or near the area that has more or less alkaline soil and a depth to water of 10 feet or less.

With few exceptions the waters of the upper valley contain only moderate amounts of mineral matter.

A very complete list of publications (mainly of the U. S. Geological Survey) giving information relating to water in the fill of mountain valleys of the western part of the United States has also been presented by Meinzer[6/]

PERTINENT GEOLOGIC FACTORS TO BE CONSIDERED BEFORE APPLYING GEOPHYSICAL METHODS, AS ILLUSTRATED IN NEVADA

In connection with geophysical prospecting for water, there are certain geologic factors that must be considered before the application of geophysical methods is made. These factors are (a) topography, (b) character of surface materials, (c) precipitation, and (d) character and structure of underlying formations, involving particular study on faulting and possible artesian systems. To explain these factors more specifically, certain of these features noted in Nevada will be used as an illustration.

Topography. - A study of the topography of Nevada (see fig. 1) reveals a system of mountain ranges and valleys running in a general north-south direction. Generally, the mountain ranges are several miles wide, with relatively wide valleys between them. The mountains rise to elevations of from 9,000 to 12,000 feet above sea level, the relief (distance above the valley floors) being generally several thousand feet.

With the exception of small areas in the northeast portion, which drain to the Columbia River, and in the southeast, the waters from which discharge into the Colorado River, the entire State is included within what is known as "The Great Basin," an extensive district lying between the Rocky Mountains and the Sierra

6/ Meinzer, O. E., work cited, pp. 291-292.

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Figure 1.—Map of Nevada showing drainage features.

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Nevadas. It is particularly worthy of note that no surface waters from this area flow to the sea, the district constituting a huge reservoir for the storing of what precipitation occurs within its drainage area.

Character of surface materials. - The character of surface materials determines to a large extent the ratio of infiltration to run-off - where porous, the ratio tends to be high, and where impervious, it tends to be low. In Nevada, the surface of the ground on the sides and floors of the valleys is commonly composed of coarse rock debris that is very pervious to water. There are, therefore, few perennial mountain streams. An unknown percentage of the rainfall evaporates at the surface, but a large part percolates downward to form a part of the ground water, much of which moves by underflow through porous materials down the gulches, and more slowly through the fill of the main valleys to their mouths. Therefore it may be stated that in general there is a gradual underground flow from the mountains down the gulches to the main valleys.

Precipitation. - Precipitation (rainfall or snowfall) within a drainage basin determines the supply of surface water, which, in turn, is the source of ground water. The precipitation in Nevada is described as follows by the Climatological Division of the Weather Bureau[1/]:

> The average annual precipitation for this section is 9.02 inches. The wettest year was 1906, with an average of 15.87 inches, and the driest was 1928, with an average of 4.87 inches. More than half of the annual precipitation occurs from December to March, inclusive. January has the greatest precipitation, and August the least. The annual amount of precipitation received in any locality depends chiefly on its elevation and its location with reference to mountain ranges. The eastern slope of the Sierra Nevada Mountains, on the western border of the section, receives the greatest annual precipitation. The lowest portion of the plateau section lies not far east of the high Sierra, and there, in the lower valleys of Pershing and Humboldt Counties and southward to the edge of Death Valley, the least precipitation occurs. The summers are clear and exceedingly dry. Thundersterms rarely occur. The number of days per annum with 0.01 inch or more of precipitation varies from 14 at Clay City to 67 at Tahoe.
>
> Snowfall is heavy in the higher mountain districts and light at lower elevations. At Marlette Lake, in the extreme west portion, at an elevation of 8,000 feet, the annual snowfall is 255 inches; while at Logandale, elevation 1,400 feet, and Clay City, elevation 2,185 feet, the annual snowfall is less than 1 inch.
>
> As in all desert or semiarid regions, heavy downpours of rain occur occasionally over small areas. These storms, locally termed "cloudbursts," may bring to the area affected as much rain in a few hours as would normally fall in several months.

In the mountains the accumulation of snow begins in the fall and continues through the winter, and snow constitutes the main source of water of the State.

1/ U. S. Dept. of Agriculture, Weather Bureau, Climatic Summary of the United States: Sec. 19, Nevada.

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The importance of conducting snow surveys, which ultimately may be used in forecasting quite accurately the flow of streams during summer months, is rapidly being recognized[8].

The percentage of surface run-off in Nevada is very much smaller than the 25 percent estimated for the Eastern states. Although the rainfall of the State is small, the percentage of infiltration is high, and the topography is such that a substantial amount of water may accumulate in certain valleys.

Character and structure of underlying formations. - The character of underlying formations, together with their structure, are very important factors to consider before applying geophysical methods to a search for underground water. Different types of rock are characterized by varying water-bearing and water-yielding capacities; and such structural features as stratification, lateral gradation, inclination of beds, folds, unconformities, joints, and faults have a marked influence on the behavior of ground water. Meinzer again has given an excellent description of these factors[9].

Nevada is well-known as a region of extensive faults, even in the relatively recent deposits that constitute the valley fill with which this work was entirely concerned. Since faults often change the path of flow of underground water, it is generally desirable in making geophysical surveys to know their location.

Certain combinations of topography and dipping aquifers sealed above and below by impermeable beds will give rise to an artesian system, in which water enters the aquifer in a cachement area in a region of relatively high elevation and percolates downward. The hydrostatic pressure thus built up by the weight of water will cause it to rise of its own accord, when tapped either naturally (faults) or artificially (drilling), to an elevation approaching the elevation of the cachement area. Frictional resistance in the flow of water through the aquifer prevents its rising again to the full elevation of the point where it originally entered. By geophysical means it should be possible in some cases to determine the course of underground wet, porous beds and thereby determine locations favorable for artesian water. In such work it is necessary to consider all possible geologic structures that might interrupt the continuity of the water strata.

The water investigations of this paper, however, deal principally with gravel beds at depths of less than 100 feet. Such beds may be capable of yielding sufficient water for irrigating moderate areas and for watering stock. Where the hydrostatic head is not sufficient to yield a flowing artesian well, centrifugal pumping commonly is feasible.

APPARATUS FOR MEASURING EARTH RESISTIVITY DIRECTLY

For making electrical ground measurements to determine the apparent electrical resistivity many devices have been used. Among these, the Gish-Rooney apparatus and the "megger" are well-known. The former measures both the current and the voltage applied to the ground, the latter the ground resistance directly.

8/ University of Nevada, Agricultural Experiment Station, Western Interstate Snow Survey Conference: Proceedings, Reno, 1934.
9/ Meinzer, O.E., work cited, pp. 102-192.

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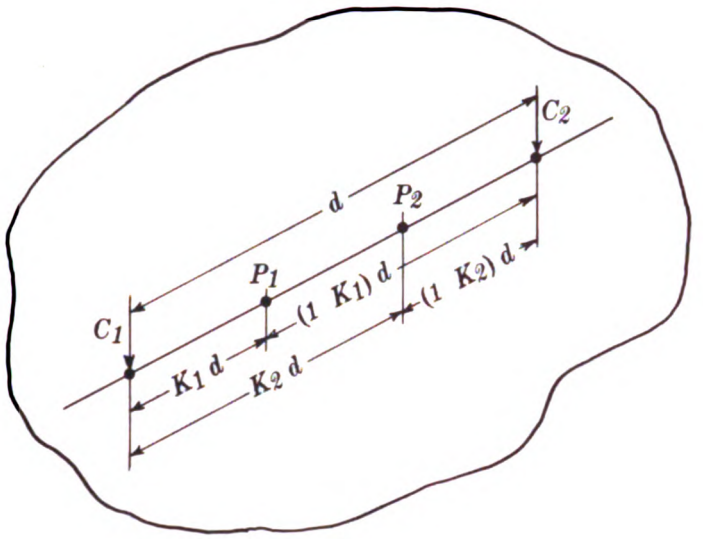

Figure 2.— Ground configuration of electrodes with P_1 anp P_2 on line of centers between C_1 and C_2.

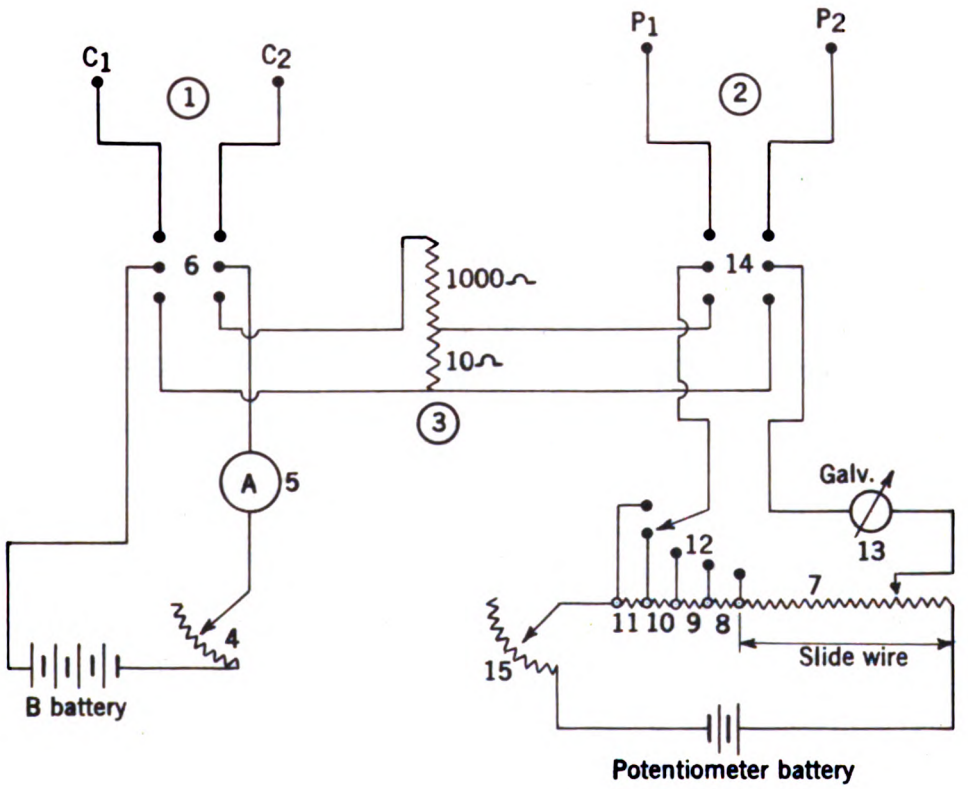

Figure 3.— Diagrammatic apparatus circuit.

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In order to reduce further the procedure of making such measurements, an improvement has been made by which it is possible to measure the apparent electrical ground resistivity directly without making any calculations involving the voltage, current, and geometrical distances. It has been found of great assistance in field procedure in that it permits immediate interpretations of the observations and will thereby avoid office computations. It has been designated the "geoscope."

Principle of operation. - To understand its principle of operation, it is best to consider the fundamental equation based upon Newtonian field distribution in a uniform isotropic medium. This relation is expressed by the formula:

$$E = \frac{I\rho}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right] \quad \text{(Volts)} \qquad \text{(Equation 1)}$$

Where E = voltage measured between two points, p_1 and p_2, in figure 2;

I = current applied to the ground at C_1 and C_2;

ρ = electrical resistivity;

r_1 = distance of p_1 from C_1;

r_2 = distance of P_1 from C_2;

r_3 = distance of P_2 from C_1;

r_4 = distance of P_2 from C_2;

$2\pi = 2 \times 3.1416 = 6.2832$.

In making geophysical resistivity observations, the electrode distance generally changes only in magnitude; that is, the ground electrodes always have the same relative spacing.

It is therefore possible to reduce equation (1) on this supposition. If:

d = distance between C_1 and C_2;

K_1 = percentage distance of P_1 from C_1 in terms of d, a constant;

K_2 = percentage distance of P_2 from C_1 in terms of d, a constant;

$$E = \frac{I\rho}{2\pi}\left[\frac{1}{K_1 d} - \frac{1}{(1-K_1)d} - \frac{1}{K_2 d} + \frac{1}{(1-K_2)d}\right], \qquad \text{(Equation 2)}$$

or

$$E = \frac{I\rho}{2\pi} C_o , \qquad \text{(Equation 3)}$$

where C_o is the constant $\left[\frac{1}{K_1} - \frac{1}{1-K_1} - \frac{1}{K_2} + \frac{1}{1-K_2}\right]$.

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Thus, for example, in the usual Wenner electrode spacing

$C_1C_2 = 3a = d$ and $a = 1/3\ d$, so equation 3 would reduce to:

$$E = \frac{I\rho}{2\pi} \cdot \frac{3}{d},$$

and

$$\rho = 2\pi \frac{E}{I} \cdot a \quad \text{(resistivity)} . \qquad \text{(Equation 4)}$$

If a is measured in feet, E in millivolts, and I in milliamperes,

$$\rho = 191.\ E.\ \frac{a}{I} . \qquad \text{(Equation 5)}$$

In the geoscope, the current applied to the ground I is generally equal to a or a simple multiple of a, $\frac{1}{1,000}$ of a. This means I is generally measured directly in milliamperes equal to a.

Under this supposition equation 5 reduces to:

$$\rho = 191.e \qquad \text{(Equation 6)}$$

A further adjustment is made by a special circuit, so that the indication E_m measured on the potentiometer is not E but 1.91 E. Hence, the instrument reads resistivity directly:

$$\rho = 100\ E_m \qquad \text{(Equation 7)}$$

where E_m is the instrument indication on the potentiometer dial.

It should be remembered that C_o, the constant of configuration, admits of many variations, some of which will be discussed later.

Simplified circuit of the geoscope. - The electrical circuits of this instrument are shown diagrammatically in figure 3. Circuit (1) is a current circuit and generally consists of a B battery, an adjustable rheostat (4), a milliameter (5), a double-pole, double-throw switch (6), and two terminals (C_1 and C_2) for applying the current to the ground.

Circuit (2) is a potentiometer circuit comprising a potentiometer battery, a calibrated slide wire (7), and calibrated resistances (8), (9), (10), and (11), each having, in effect, a resistance equal to that of the slide wire. A contractor switch (12) permits raising the voltage in units of 100, and the slide wire subdivides the 100 units on it into single units. A galvanometer (13) indicates when the applied and adjusted voltages are equal. A double-throw switch (14) permits connecting the potentiometer circuit either to P_1 and P_2 or to circuit (3).

Circuit (3) consists of high resistance of about 1,000 ohms connected in series with 10 ohms, and it may be classified as a conditioning circuit. This circuit is used as follows:

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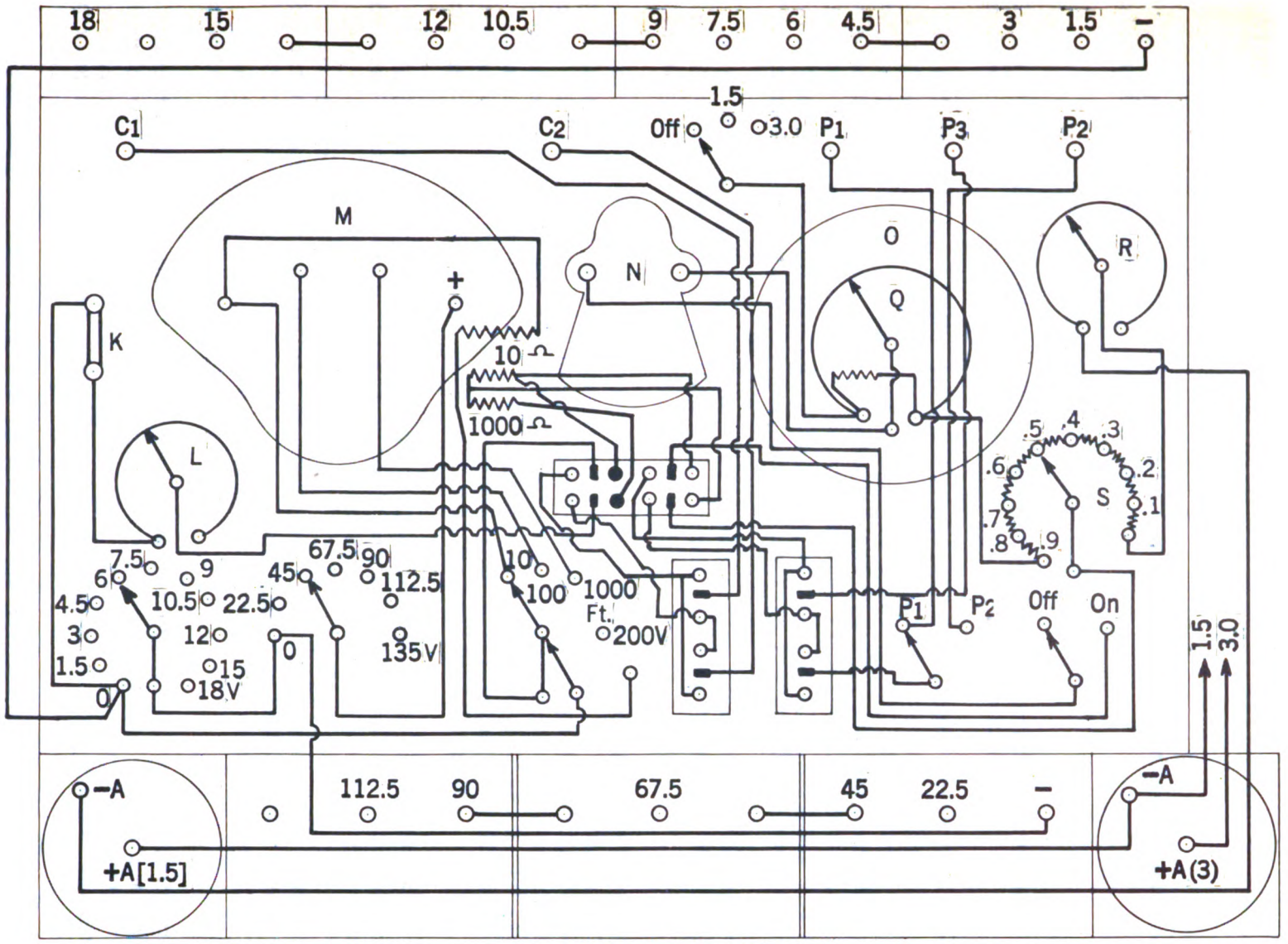

Figure 4.— Actual circuit of geoscope.

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Examining the formulae for resistivity, it is noted that, for example, in equation (6):

$$\rho = 191 \cdot E$$

If a ground voltage of, for example, 100 millivolts had been measured from equation (6): the electrical resistivity

$$= 191 \times 100 = 19{,}100 \text{ ohm-centimeters}$$

would be the resultant resistivity. The potentiometer scale of the instrument, therefore, should read not 100 millivolts but 191 millivolts.

This is done very simply in the instrument as follows: With the double-throw switches (6) and (14) down and with 10 milliamperes on 10 ohms, the voltage applied to the potentiometer circuit would be 100 millivolts. The slide-wire potentiometer is now set, not for 100 but for 191, and the current in the slide wire is adjusted for a balance of rheostat (15) in this setting. It is obvious that now for any ground voltage the instrument will multiply all of them by this constant factor, 1.91, and thereby measure resistivity directly.

After this adjustment is made, the conditioning circuit is disconnected and the double-pole, double-throw switches (6) and (14) are thrown to the operating position.

After the ground contact connections have been measured or laid off for their proper intervals, the current in circuit (1) is adjusted to this value. If, for example, CC^1 is 50 feet, the current applied to the ground is 50 milliamperes. With this applied current the potentiometer is balanced and its reading will be the apparent earth resistivity. Sometimes due to the character of the ground, it may be more convenient to adjust the current to 5 milliamperes instead of 50, in which case the potentiometer reading should be multiplied by 10.

Actual circuit of the instrument. - The circuit actually employed is shown in figure 4. The circuit (1) has three B batteries tapped for 22.5, 45, 67.5, 90, 112.5, and 135 volts. In addition to this battery there is still a smaller one that permits voltages of 1.5, 3, 4.5, 6, 7.5, 9, 10.5, 12, 15, or 18 to be used in conjunction with the higher voltages. The milliameter has three ranges, 0-10, 0-100, 0-1000 with also a voltage connection for testing the condition of the batteries. If necessary, more batteries or control rheostats may be inserted by opening the link (K) in this circuit.

Circuit (2) uses two Columbia dry cells for activating the potentiometer current circuit. Switches are arranged so that connections to the ground can be made either between P_1 and P_3 or P_2 and P_3. Suitable current controls and reversing switches also are placed in those circuits to compensate the usual self-potentials of the earth.

It has been found that there is a distinct advantage in using conditioning circuit (3) and not a standard cell for adjusting the current in the potential circuit, as in desert regions such as Nevada the operating temperature may be well over 100°F., at which temperature the standard cell ceases to function properly.

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The same remarks also apply to subzero weather. It must always be remembered that the accuracy of any measurement by a set of instruments is not greater than the poorest of the instruments, which is generally the indicating instrument, in this case the milliameter. It is therefore apparent that little or no accuracy is lost by utilizing the milliameter for calibrating the current in the potentiometer current circuit.

For convenience the batteries, instruments, and switch gear are placed in an oak box (fig. 5). In actual field operation this instrument may be set on a plane table.

For making shallow measurements, only an instrument operator and an assistant are required. If, however, rapid progress is to be made, especially if the measurements extend to a considerable depth, an instrument operator and four assistants should be available to expedite adjusting distances and making ground contact connections.

METHODS OF USING ELECTRICAL RESISTIVITY FOR CORRELATING GEOLOGICAL STRUCTURE

To aid the miner and geologist it is not at the present time practicable to use in resistivity methods the elaborate theories of electrical conduction in space. Such theories postulate certain conditions in nature that may be only local in character and not universally applicable, and such postulates often disregard other factors that may modify the conclusions. From the practical angle, it is generally not necessary to use such a theoretical procedure to acquire the necessary subterranean information.

A certain pattern of measurements, for example, will show definite characteristics peculiar to each locality. Once the peculiarities have been found and identified, they are easily recognized wherever they recur. In other words, it is not generally necessary to know the mathematical equation of a complex geological system in order to be able to recognize the distinguishing features, examples of which will follow.

So it is with the practical application of electrical methods of prospecting, using the electrical resistivity methods. If, for example, in a certain district the geology is known by surface exposure, drilling, or mining operations, it is only necessary that the electrical characteristics of such a structure be determined by the proper resistivity measurements. Once such a key to the structure has been established, it can generally be followed even though it be covered with overburden. It is true that such a picture will not be as clear if screening factors are extensive; yet, if prominent characteristics exist, such characteristics will often tend to persist and therefore be identifiable.

For practical purposes, certain simplified assumptions regarding easily measurable numerical values must be made. For this purpose, the assumption of an ideal isotropic medium may serve very well and is the first assumption to be tried. The conditions of current and potential distribution, coupled with the patterns of symmetry, are the best guides to subsurface interpretations. Where practicable, geological studies of the continuity of water-bearing beds must always be made as a check on the geophysical interpretations.

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Figure 5.— Photograph of geoscope.

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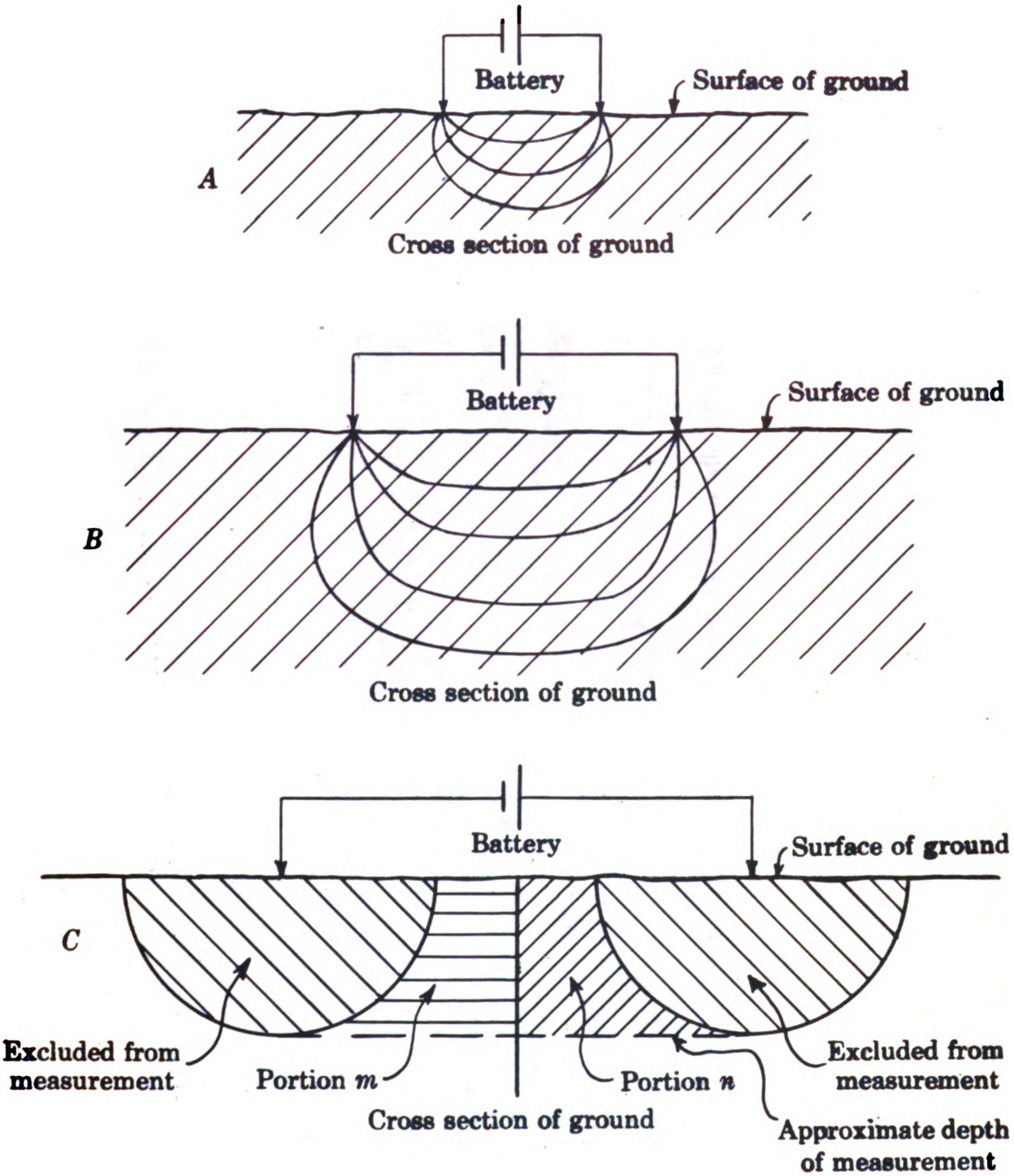

Figure 6.— Principles of ground resistivity measurement.

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Figure 7.– Steven Young's ranch with sump in the middle ground.

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The use of models and small-scale analysis, using materials other than the ground in question, on the whole has been unsatisfactory. The reason may be ascribed to the fact that such laboratory equipment does not faithfully reproduce many of the characteristics existing in the field, which serve to delineate and identify geologic structures.

ADVANTAGE OF KNOWN GEOLOGICAL STRUCTURES TO GEOPHYSICS

Generally, in a district having geological characteristics of particular interest there exist certain portions that have been carefully explored and described. It is of the greatest importance in beginning work in a new district that parts with known geological characteristics be defined carefully and measured geophysically.

Similar geophysical reactions in the same geological district generally will define the same kinds of geologic structure. The better the detailed geology is known, the better will be the foundation for the geophysical work and the ability to interpret the results. Experience in making geophysical observations will determine what measurements should be made to define best the structure in question. An effort is made in this paper to explain some of the factors in certain geological problems, especially as they are connected with the discovery of water.

FIELD MEASUREMENTS FOR WATER

To those not familiar with the principles of ground-resistivity prospecting, the following notes may be of assistance in understanding them. Figure 6, part A, shows two electrodes with a battery for applying current to the ground. Part B shows the same electrodes separated at a greater distance. It will be noticed that the main volume of current now penetrates deeper into the ground. So, by changing the spacing of applied ground-current electrodes, the depth to which prospecting is observed is controlled.

A still further refinement of observations is made in that the ground is electrically partitioned (part C), so that the effect of the ground near the stakes is excluded, and portion m may be compared to portion n. If the two are identical, there is no change of structure; if they diverge, then geological dissimilarities exist. The ability to analyze and classify such anomalies constitutes one of the problems of the field geophysicist.

In starting observations in places where no geophysical measurements have been made, it is best to make observations on conditions that are known to disclose characteristic geophysical patterns.

At a ranch known as the Steven Young ranch, near Lovelock, Pershing County, such preliminary observations were made. Two features here offered valuable information in this preliminary study.

The first consisted of a pump used to supply water for irrigation purposes, a picture of which is shown in figure 7. Each day water was pumped, by a 25-horsepower electric motor attached to a 6 inch centrifugal pump, for a period of

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10 to 12 hours at a rate of about 600 to 800 gallons per minute. After 10 hours pumping the draw down was about 4 feet. The lowering of the water level showed a thin gravel bed draining in from the east as the source of the water. (Point marked A on resistivity map 1, fig. 8.)

The second feature consisted of a dry ditch immediately to the west of the pump, shown in figure 9. At one time, several decades ago, this ditch was part of a power plant operated by water from the Humboldt River. It was about 14 feet deep and served well to show the beds of clay, tuff, volcanic ash, and gumbo, that make up the upper part of the valley floor.

The results of irrigation are shown in figure 10. The desert is in the foreground and an alfalfa field in the nearer background of the picture. From 6 to 8 tons of alfalfa per acre can be grown per year on the ground once it is irrigated.

Not far from this point, to the north, is the bed of the Humboldt River (see fig. 11). Although the bed of the river here is about 20 feet below the general ground level, it is cracked and dry. It is not uncommon in this district to sink a well several feet in dry gravel; but on puncturing a bed of clay, water will rise to a level within a few feet of the top. (Verified in drill hole, resistivity map 1, fig. 8.) The region may be considered to consist of various gravel beds carrying more or less water under different heads. The main portion of the ground was found to be moist clay, which is almost impervious to the flow of water. There is in this district, also, a definite correlation between snowfall and runoff, which ultimately determines the amount of water available.

RESISTIVITY SURVEYS NEAR STEVEN YOUNG'S RANCH

With a starting point on Young's ranch, electrical-resistivity measurements were made on a north-south line (see C on resistivity map 1, fig. 8). Stations 14, 13, 12, 11, 10, 9, 15 and 16 were measured 72 feet apart and depth measurements made by increments of 6 feet. The value of resistivity on map 1 was plotted, not in the usual way, as directly related to depth, but as related to topography, in other words, where on the surface to drill to strike the resistivity characteristics in question. However, in the field the results were plotted in the usual way, as is seen from figure 12, showing the observations north and south of point 13. On this graph it will be noticed that to the south a very abrupt rise of resistivity occurs at a depth of 18 feet. A hole was drilled with a 4-inch post-hole auger and showed gravel at 18½ feet immediately following a bed of clay. The log of this drill hole (No. 2) was:

	Thickness		Total depth	
	Ft.	in.	Ft.	in.
Loam.....	7	10	7	10
Clay and loam.....		2	8	
Clay.....	1		9	
Sand.....	4		13	
Clay.....	1	6	14	6
Sand and clay.....	4		18	6
Gravel.....	---		18	6 +

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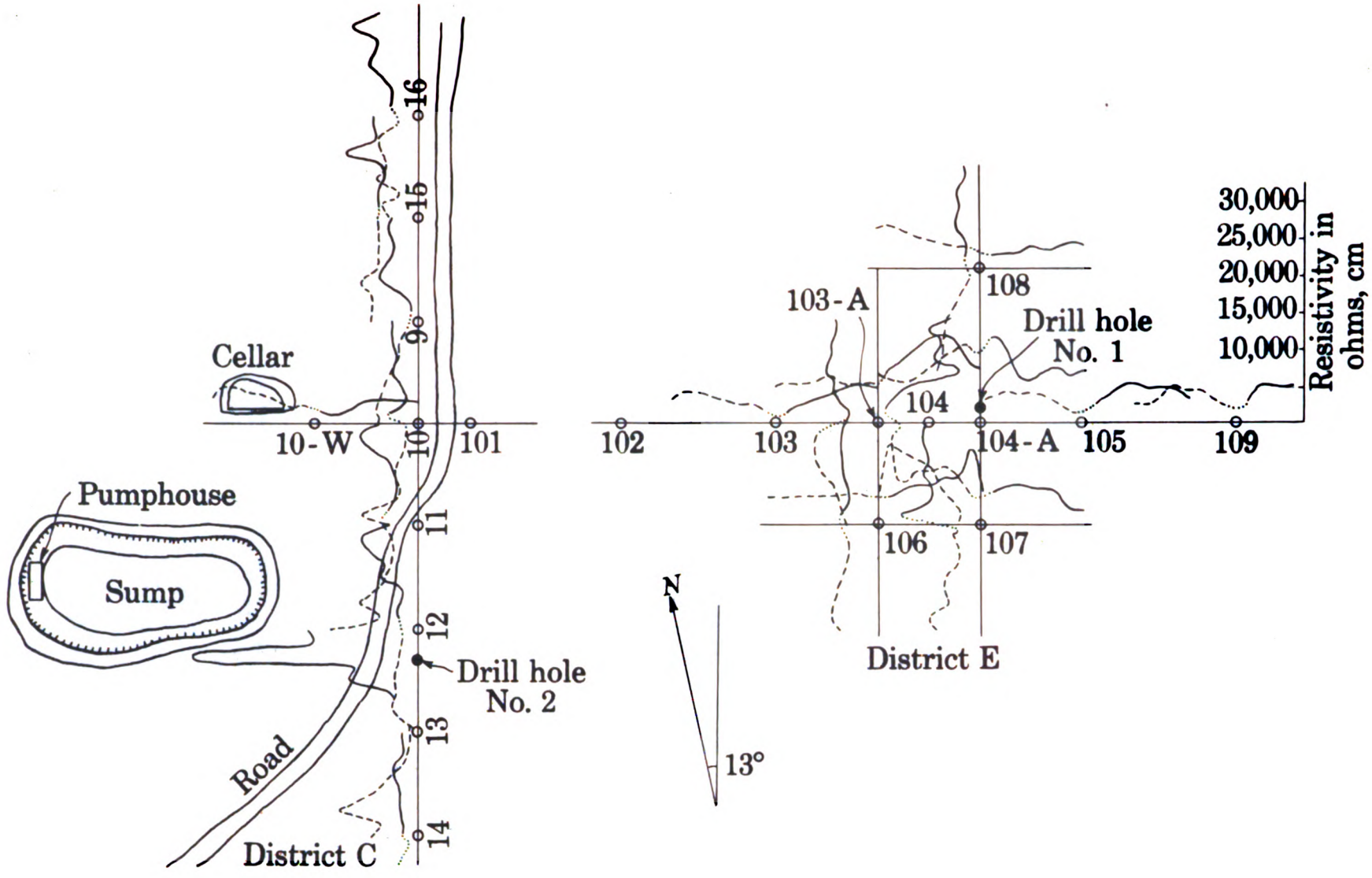

Figure 8.—Resistivity map of Steven Young's ranch, Humboldt Basin district.

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Figure 9.— Dry ditch, showing surface geology.

Figure 10.— View showing the contrast between irrigated and desert ground.

Figure 11.— Bed of Humboldt River west of Steven Young's ranch.

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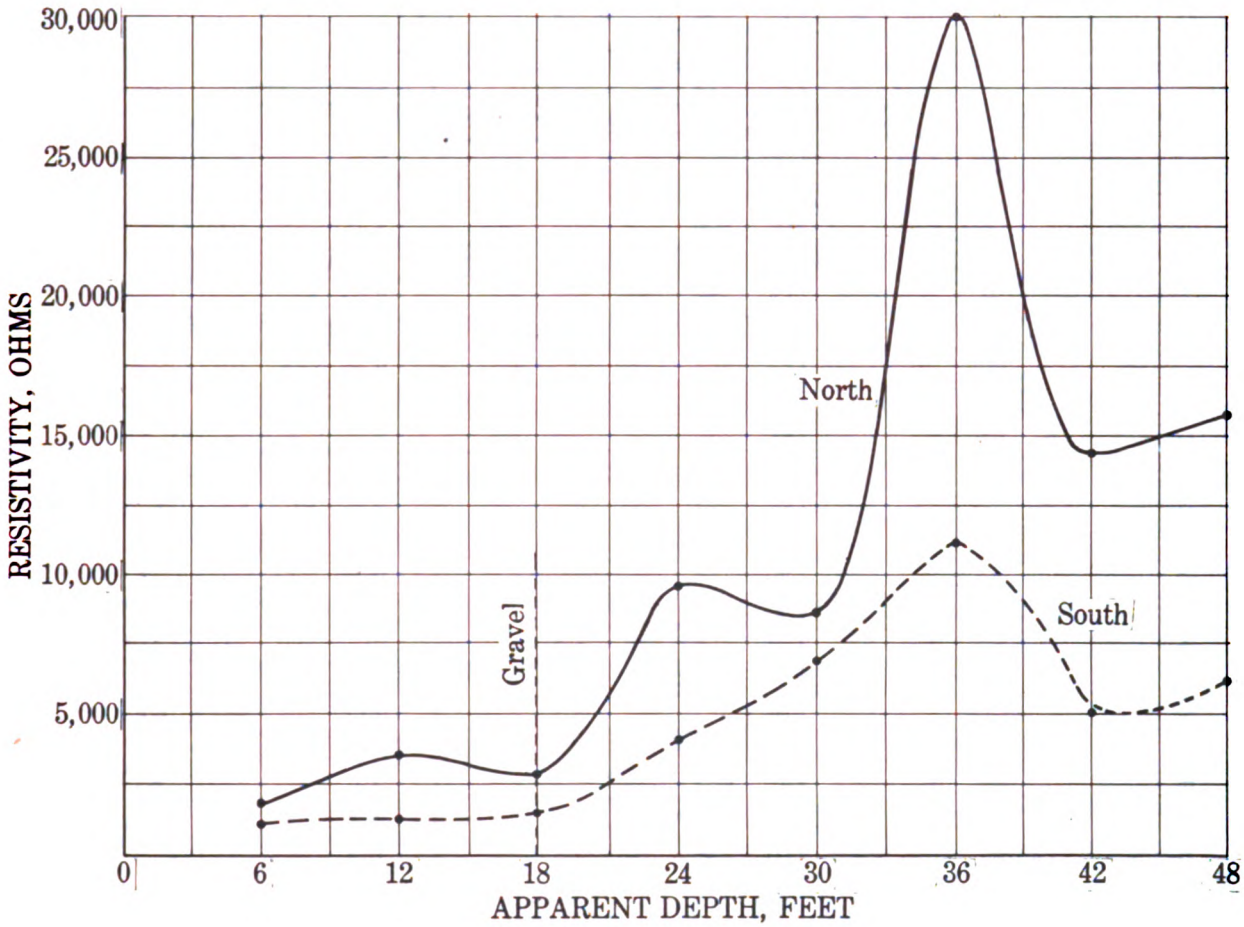

Figure 12.—Graph of resistivity shown at station 13 of fig. 8.

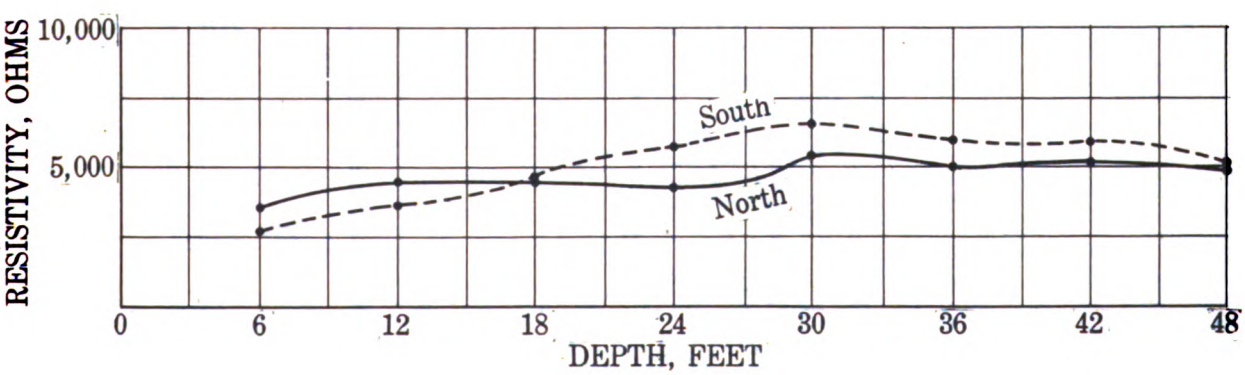

Figure 13.—Typical resistivity curve in Humboldt Valley, Nev.

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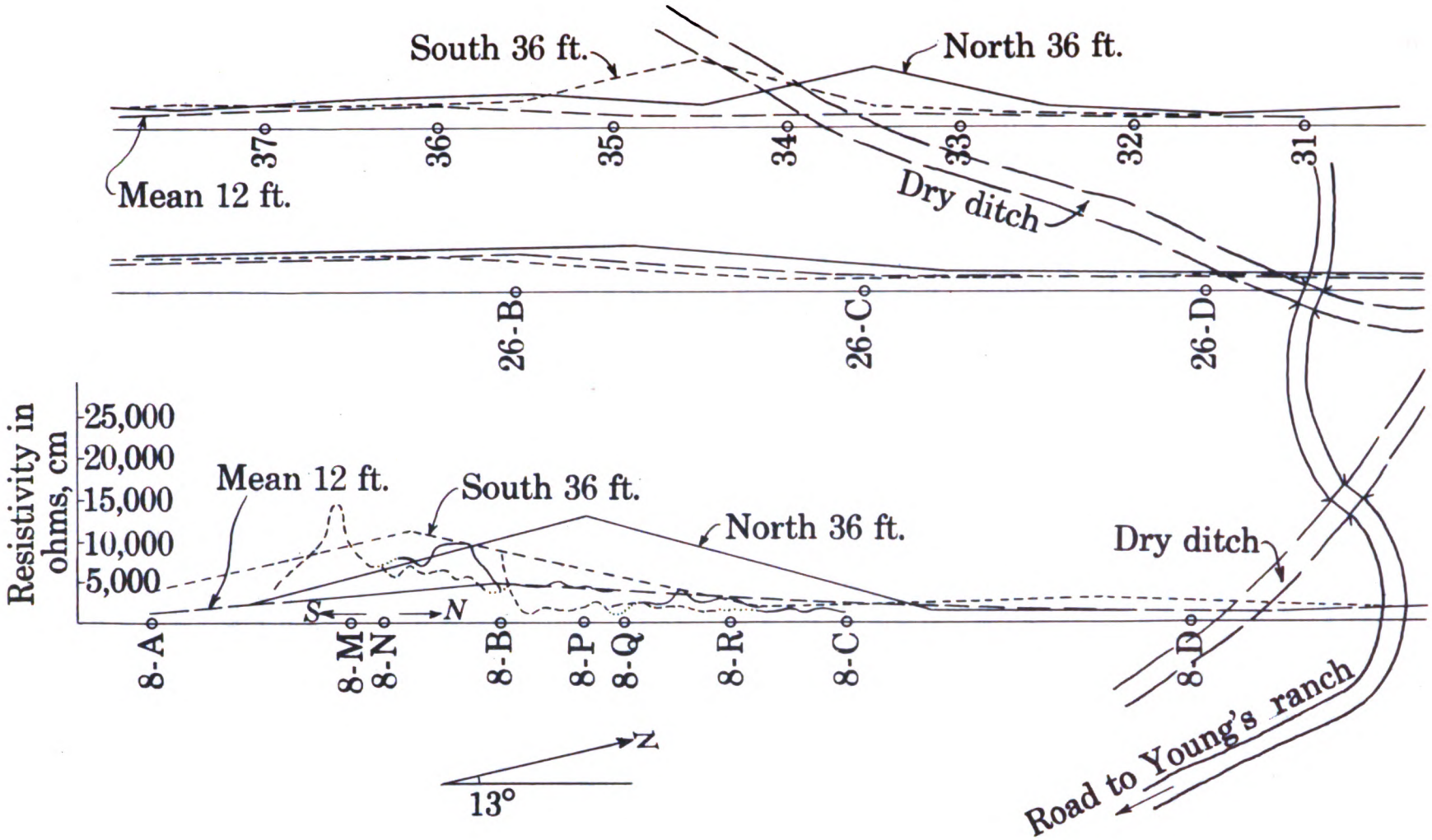

Figure 14.— Resistivity map of area 2, Humboldt Basin district.

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From its nearness to the pump, it is evident that the gravel bed is the source of water. It may be noted that the sharp change in resistivity occurring at 18 feet is similar to observations made by the writer in Canada in 1929, where the resistivity high was also attributed to water-bearing sand and gravel beds.

A typical resistivity depth curve is shown in figure 13. A striking feature is the low value of resistivity of this material, being of the order of 5,000 ohms. The surface indications might lead to the assumption that it would be almost impossible to force any current into the ground at all. However, for most places in the valley, the 90-volt B battery sufficed to deliver enough current for good resistivity determinations. Iron stakes 30 inches long, instead of the customary 12 inches, were used.

The curve affords a very striking illustration of ideal conditions in that it shows a uniform isotropic material to a depth of 48 feet, which, from likeness to other areas, may mean a deep rich soil having a long productive life. The mountain ranges so protect it that the winds cannot carry this top soil away.

In these resistivity charts the full lines are resistivity observations made from south to north and from west to east. The dotted lines are from north to south and east to west. Before drilling is decided upon, the same interpretations should be indicated by both measurements and many additional confirmatory observations should be made.

Measurements made in district D showed evidences of gravel, but since the location was so near the sump, it was decided to go away from it a considerable distance. Accordingly, district E was examined.

Following along the horizontal (east-west) line of stations 102, 103, 103-A, 104-A, 105, and 109, it is noticed that the resistivity gradually increases in this area until it reaches a maximum at about 104-A, after which it decreases again. Corroborative evidence also was obtained on the north and south line by stations 107 and 108.

Since this place was about 500 feet from the sump, and also since there was no resistivity continuity between district C and district E, it was selected to be drilled for gravel and water. A churn drill was used, and gravel was found at a depth of 16 feet 9 inches, water at 25 feet, and a gravel bed over 18 feet thick. In this district all stations were measured at depth intervals of 6 feet, beginning with 6 feet and stopping at 48 feet.

This method of ground examination is rather slow, faster progress being possible by measuring at regular intervals of 72 feet to a constant depth of 12 feet and 36 feet. The surface or 12-foot measurement determines the character of the overburden and the 36 feet the conditions farther down. Figure 14 shows an area so examined near the camp, about 3 miles from Steven Young's ranch. Of the many measurements taken, very few had a resistivity of over 10,000 ohms. Where these places were measured in detail there was not much promise of large gravel beds. Furthermore, there was but little difference in resistivity of the soil between the depth at 12 feet and 36 feet. This shows that considerable time must be spent in covering barren territory, which enhances the cost of such work.

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In a district in the section north of Steven Young's ranch, shown in resistivity map 3, figure 15, a large territory between stations 210 and 203 on an east-west line as well as 207-A and 207-O on a north-south line showed an average resistivity of over 15,000 ohms, which tapered off to about 5,000 ohms at the edges.

The gradual approach to a gravel bed is seen from observations along stations 202-B, 202-A, 202, 202-M, and 202-N. It is seen that the average resistivity gradually increases and then decreases again, with the center between stations 202-M and 202-N. The same is noticed along stations 204-B, 204-A, 204, 204-M, 204-N. This therefore would indicate the position for the deepest or thickest portion of the gravel bed.

Inspection of the data at the 36-foot apparent depth level along the east-west line shows considerable variation if the measurement is made toward the west or east at the boundary of the deposit. On the other hand, such anomaly does not occur at stations 207-C, 207-B, 207-A. This might indicate a very gradual dip of the deposit to the north and a more abrupt terminus at the east and west boundary of the gravel deposit. It agrees with the elementary principle that the influence of a foreign material is roughly proportional to the extent to which this material enters or leaves that portion of the electric current field in which the greatest curvature exists.

ANOMALOUS CURRENT DISPERSION

It is now usually admitted that it is generally advantageous to use the apparent ground resistivity as based upon the ideal isotropic field distribution of the current for an index number in classifying formations and also for interpretive purposes.

Under this assumption certain geologic structures may give anomalous results. One such anomaly occurs when there is a concealed steep contact, such, for example, as might exist between gravel and clay beds (see fig. 16). Here the surface resistivity of the clay is low and that of the gravel is high.

In using the partitioning method, it will be seen from figure 16, part A, that the potential between P_0 and P_2 will be small, since the path of the main current is A and not B. Consequently, the computed resistivity will be low in this interval instead of high. Furthermore, there is more current between P_0 and P_1 than between P_0 and P_2, and its computed resistivity will therefore be higher instead of lower, although the actual resistivity is generally lower between P_0-C_1 than between P_0-C_2.

As the dividing point is moved farther to the left (part B, fig. 17), most of the current is in the interval B and little at A. This would tend to indicate a high resistivity between P_0 and P_1 or P_2 instead of low values as are actually the case.

These results may be considered to be due to the anomalous current distributions that occur at sharp steep boundaries at shallow depths. As soon as the partitioning point has passed through this zone the readings on both sides again have values of the same order.

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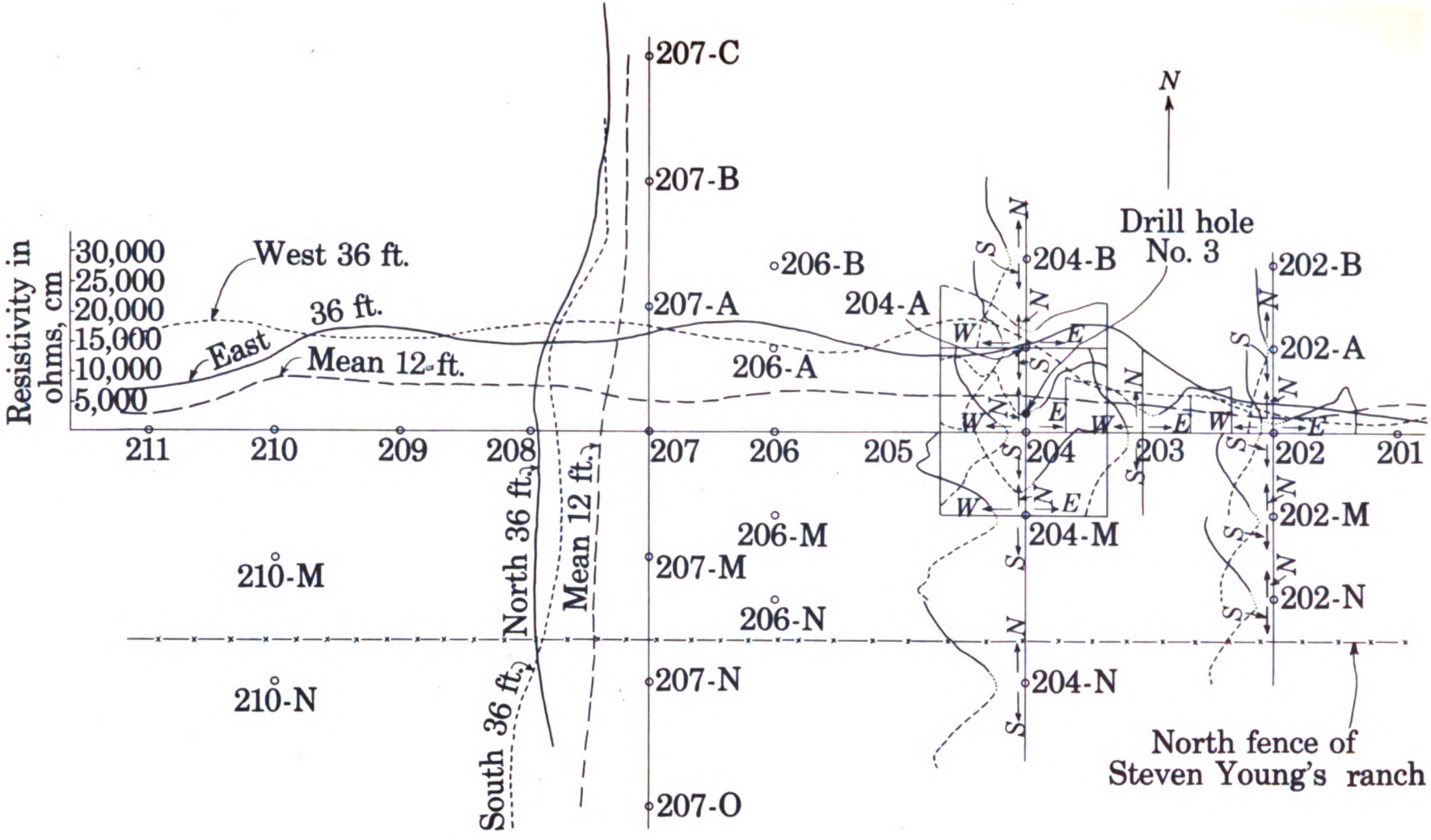

Figure 15.—Resistivity map of area 3, Humboldt Basin district.

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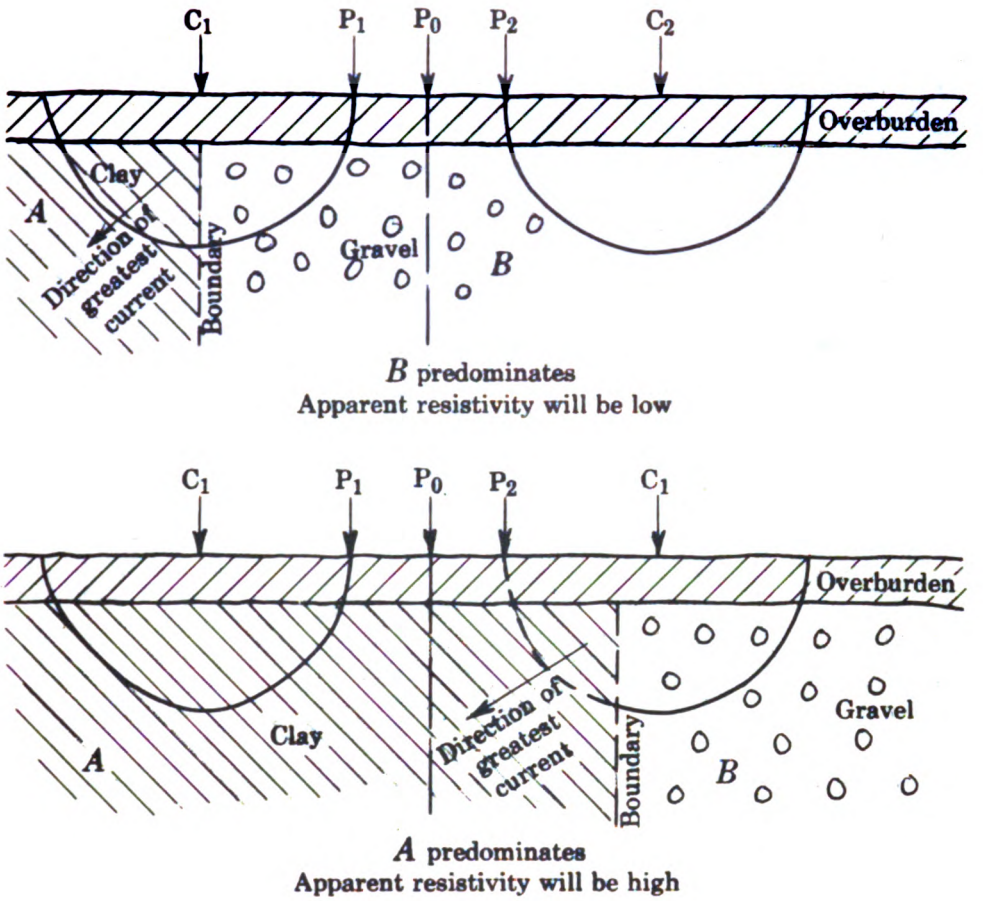

Figure 16.—Anomalous current dispersion.

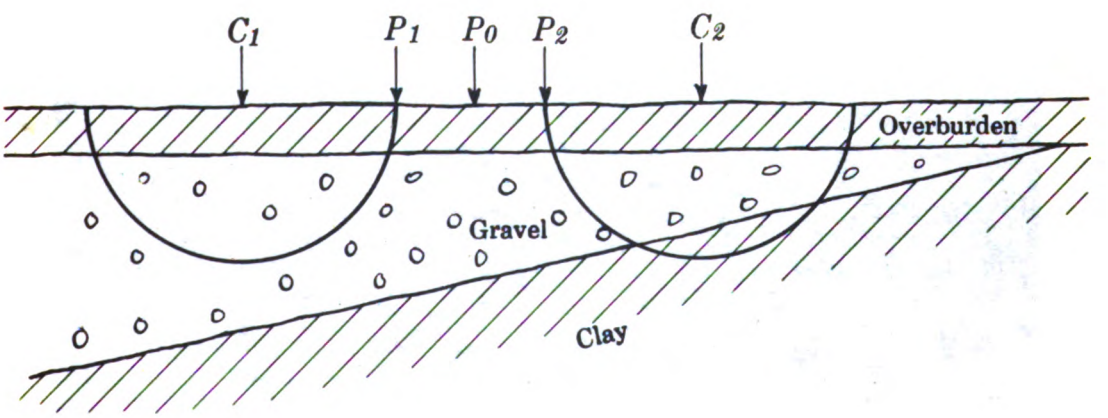

Figure 17.—Gradually dipping bed of gravel north of area 3.

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Figure 18.— House covering Diesel-powered pump on Pitt ranch.

Figure 19.— Typical area underlain by a large water-bearing gravel bed.

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Figure 20.— Field party in operation in a district underlain by water.

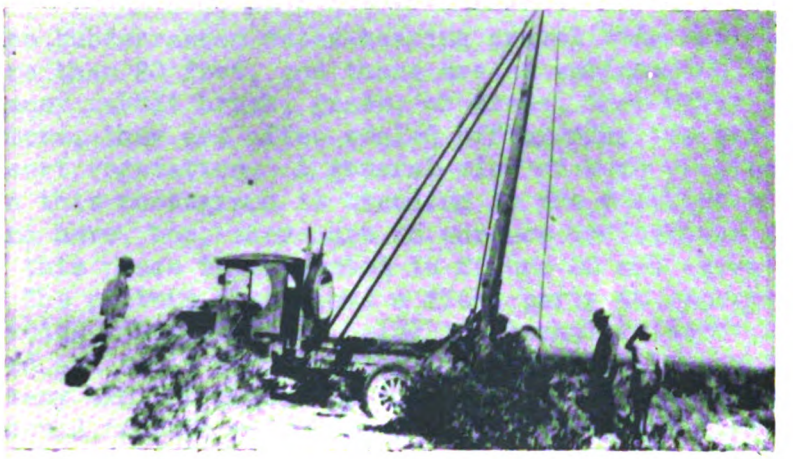

Figure 21.— Well-drilling rig.

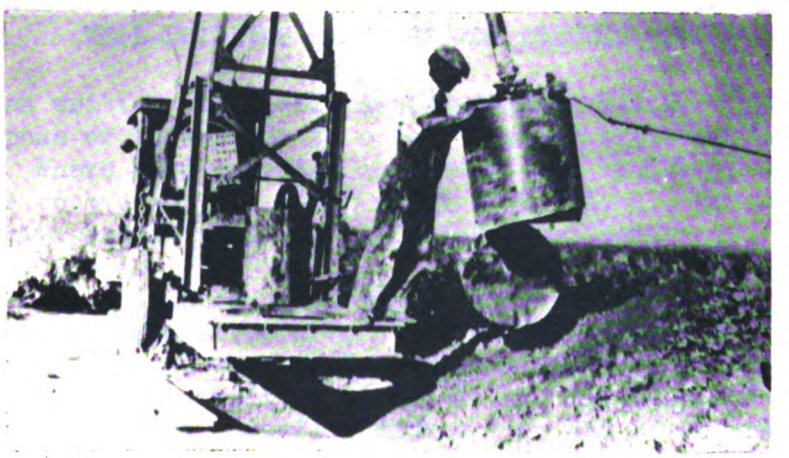

Figure 22.— Buckets and blades of drilling rig.

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It is apparent that such results may give information concerning the shape of the contact between the gravel and the clay.

To the north the contact is not vertical but nearly horizontal with a gradual dip, figure 17. A churn hole, No. 3, was drilled in this district to prove the existence of gravel beds and water. The log of the well shows both gravel and water.

Still another territory was examined directly west of Lovelock on the Pitt ranch. Here a Diesel engine, belted to a deep-well centrifugal pump, was used to obtain water for irrigating (see fig. 18). This water probably had its origin in Seven Troughs Canyon. Here, as on the section of Steven Young's ranch, high-resistivity regions were measured at the pumping station from which most of the water was drawn.

Successful application of geophysical methods for finding water-bearing gravel beds sufficiently large to furnish water for irrigating moderate tracts of land is indicated by the promising results of the work in this district.

Some of these subterranean water-bearing gravel beds are covered with alluvium to a depth of more than 20 feet, and there are no surface indications, such as taller sage, greener rabbit brush, grass, or trees, that would lead to their discovery. Furthermore, they are often sealed off by clay too dry to support more than ordinary desert vegetation. A general view of such an area is shown in figure 19. The truck in this photograph is standing in the district of the resistivity map (fig. 15), and here, too, there are no surface indications of water beds below. A nearer view of this place is presented in figure 20 and shows the sparseness of the vegetation. The picture also shows a field party in operation. As an illustration of possibilities, this area has below it at shallow depth a very large water-bearing gravel bed and would furnish water to irrigate a moderate-size ranch. No doubt there are many similar places in this district which by proper exploration and development could furnish water for a number of subsistence homesteads.

Cheap electric power is one of the requisites for developing such natural resources. The rates charged in the district are too high to permit proper development of its water resources.

WELL-DRILLING MACHINES FOR DROUGHT RELIEF

Much has been written about well drilling and drilling rigs, and it is therefore not the purpose of this paper to enter into any extended description or discussion of them. Where hard material is encountered the churn drill is usually the cheapest, the cost of a hole being about $3 per foot. If the well is to be dug by hand and timbered it will cost about $20 per foot.

However, in many instances, when the question is one of getting water and not of determining geologic structure, other drilling devices are to be preferred, especially in places where only unconsolidated sediments will be encountered, as in many of the valleys of Nevada and the adjacent States. What is known as a cesspool digger typifies such a rig, and it was at the writer's suggestion that this method was adopted for digging the wells.

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Essentially, the cesspool digger consists of a truck with a mast or ladder carrying a sheave for withdrawing the bucket from the hole (see fig. 21). An apron is attached at the rear of the truck carrying what may be termed a ring gear or bull wheel for a rotary drive. Neill McGill gives the following description of the rig:

A cylindered bucket is driven by a square 2-inch nickel-steel rod, which is used to drive approximately the first 18 feet of the hole. From that time on the rod telescopes into extra-heavy 3-inch pipe and is connected to the pipe by inserting iron pins. When additional depth of hole is required, an extra joint of pipe is put on. The rig is equipped with enough pipe to dig to a depth of 105 feet. This rig has just completed a hole to a depth of 90 feet east of Eureka.

The rig has a 14-inch sheave at the crown of the mast or ladder, and a drum that is used for lowering and hoisting the bucket out of the hole.

The bucket is equipped with two sets of digging blades (see fig. 22). One set is attached to the bottom of the bucket by means of bolts and extends about 3/4 inch beyond the sides of the bucket. An additional set of blades is attached to the top of the bucket and may extend beyond the diameter of the bucket any distance required, up to a point where a 6-foot diameter hole can be dug. These blades act as reamers and cut the dirt from the sides of the hole into the top of the bucket.

Thirty revolutions per minute is average speed. In good digging, a much faster speed can be attained.

At such a speed, in ordinary gravel, a hole 25 feet deep can be dug in from two to four hours. The following information may be of interest: In excellent digging material, a hole was dug with this rig to a depth of 50 feet in 1½ hours; in a 90-day period, the rig dug 32 water wells to an average depth of 45 feet, and in addition to that moved a total distance of 600 miles.

Wm. O. Vanderburg adds the following description of a similar rig:

The machine is similar in design and operation to the auger equipment used by telephone companies for digging telephone post holes. It is mounted on a 3-ton truck and is readily portable.

The machine has considerable range of application in drilling dry places and in wet ground. If drilling is done in wet ground or in extremely dry material the openings behind the cutting blades must be equipped with leather flap valves, to permit the material ingress into the bucket but preventing its egress. The advantage gained from the use of the drill in sinking wells and test holes are low cost, speed, and representative samples of the material drilled.

The drill will cut soft shale and any gravel readily providing it is not cemented too firmly and the boulders in the latter do not exceed the width of the opening behind the cutting blades, which is about 6 inches. If

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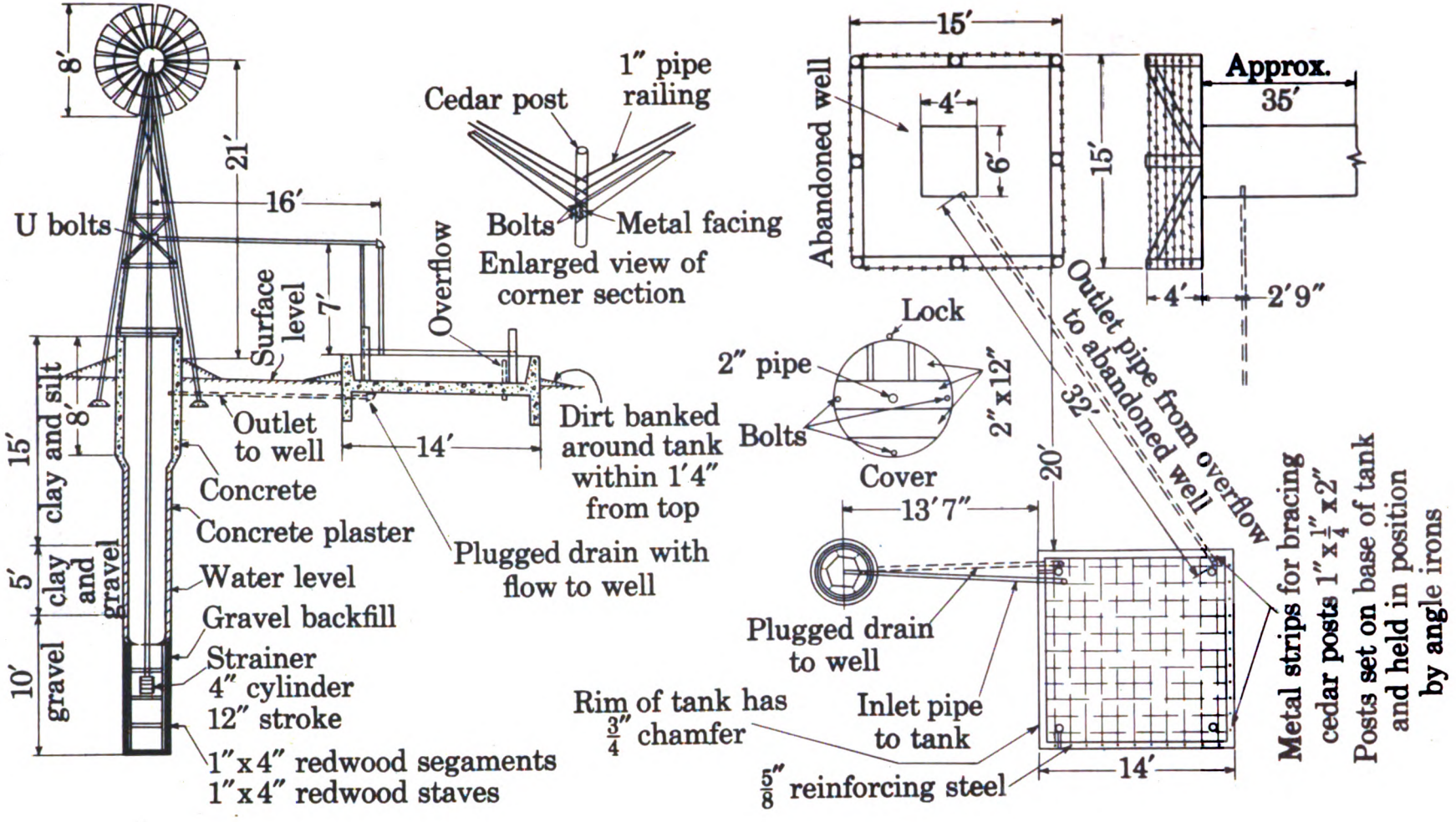

Figure 23.—Cross-sectional elevation and plan of a well.

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boulders larger than 6 inches are encountered they must be removed by hand, and for this purpose a man is lowered into the hole, if the hole is shallow. In some cases, it is easier and safer to start a new hole. Suitable casing could be employed to minimize the hazard of lowering a man into the hole to loosen a boulder.

In the Atolia field a machine of the type described was used for placer sampling. The average thickness of the gravel was about 25 feet, with a minimum of 12 feet and a maximum of 45 feet. The work was done on a contract which specified 1,000 feet of holes averaging 30 feet deep at a rate of 35 cents per foot of depth. The company expected to drill about 200 feet per day with two rigs, but owing to the presence of some boulders the average progress was about 150 feet per day.

It was only after such modern methods were used for digging wells that real progress was made in drought relief in White Pine County, Nev.

At first it was remarked that a machine of this nature would not permit sufficient labor to be employed from the relief rolls. However, when actual drilling started it was found that more men were needed to follow the drill and put in the proper casing and cement finish. The net result was that 10 wells were completed for the price of one hand-dug, and the effectiveness of the drought-relief service was considerably augmented.

After drilling a well considerable supplementary work is necessary before a project can be considered completed. Neil McGill has prepared figure 23, showing a complete well lay-out. He also kindly furnished the writer with the general notes and cost data on a typical well-drilling operation, shown in table 1.

TABLE 1

General Notes

Started - August 30, 1934.
Completed - October 15, 1934.
Size - 38 inches.
Depth - 30 feet.
Depth of water - 12 feet.
Equipped for - cattle.
Equipment - one 21-foot tower and 8-foot wheel, one 14 by 14 by 2-foot concrete storage tank.
This is an excellent well; it can water 500 or more head of cattle, a benefit to three or more ranchers, and is an excellent example of workmanship. Opens up 4 square miles of range land. Feed consists of greasewood, black sage, white sage, and valley grass.

Cost Data

No.	Description	Unit	Price	Amount
64	Cement.....	Sack	$ 1.10	$ 70.40
2	Lime.....	do.	1.47	2.94
716	Reinforcing steel.....	lbs.	.0375	31.36
500	Barbed wire	Spool	5.25	1.99
14	Cedar posts	each	.485	6.79
	Misc. pipe, lumber, nails, etc.			46.71
20	Sand and gravel....	Cu.yd.	5.10	102.00
1	"Aeromotor" windmill, 8 ft. wheel..	Each	120.79	120.79
	Gas and oil			3.79
	Labor.....			462.63
	Truck hire.....			239.31
	Rental drill machine (1 day)	Each day	20.00	20.00
	Total revised cost.....			$1,108.71

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ELECTRICAL RESISTIVITY MEASUREMENTS ON ARTESIAN WELLS

Although most of the work was directed primarily toward finding water at shallow depths of less than 50 feet, some preliminary work was done on artesian water. Resistivity measurements were made in the vicinity of Las Vegas, Nev. on Lorenze's artesian wells (see fig. 1). The surface outcropping was limestone, but in most cases sufficient alluvium was present to permit making electrical contacts without much difficulty.

The characteristic feature of the curves is their saw-tooth form (fig. 24) indicating alternate beds of gravel and clay. Considerable local geological structural variations, such as cross-bedding, exist at shallow depths up to about 86 feet. After that the beds become bigger and more easily identifiable and of greater importance as aquifers.

The question remains: To what depth and how easily can the characteristic features of deeply covered aquifers be identified? That such beds can be located by resistivity methods was also shown by the resistivity chart of Bertine's well in Hot Creek Valley (see fig. 1). The same saw-tooth characteristics also were observed on a resistivity curve (not corrected for topography), especially near the bottom of the well where water was struck (see fig. 25). Here the surface material was the usual valley alluvium having a resistivity of about 1,500 ohm-centimeters. Apparently the small gravel beds between clay beds were not sufficiently identified and recorded in the log of the well. It is very interesting to note the change of the resistivity curve at many of these places of contact.

There are now enough data on hand to show that artesian structure is so well characterized that barren territory down to depths of some 350 feet can be excluded. The structure can be identified, although it cannot be definitely determined whether it carries sufficient water or under how much head unless the beds can be traced to the origin of the water.

Geophysical research of this nature requires constant drilling to identify the electrical characteristics of the ground and to classify them properly. Probably no money could be better invested in a combination of geophysical and geological research than that bearing upon subterranean water.

It is hoped that it will be possible to trace such aquifers to the source of their water and to determine where most water can be obtained from them without silting the wells. An aquifer generally has coarse gravel and rock at its outcrop on the side of a mountain, the finer gravels and sands being at its toe. Although the initial pressure is greatest at the lowest point, the sand which is washed into the well with the water often very quickly reduces the porosity of the bed around the well and fills the pipe, thus shutting off the well.

CAMP PREPARATIONS AND EQUIPMENT

Field procedure in geophysical prospecting differs from geological field work in two principal respects. In the first place, the instruments are not as simple and are more bulky than a geologist's tools. They may have a precision greater than that of the ordinary physical laboratory apparatus, and some are very delicate

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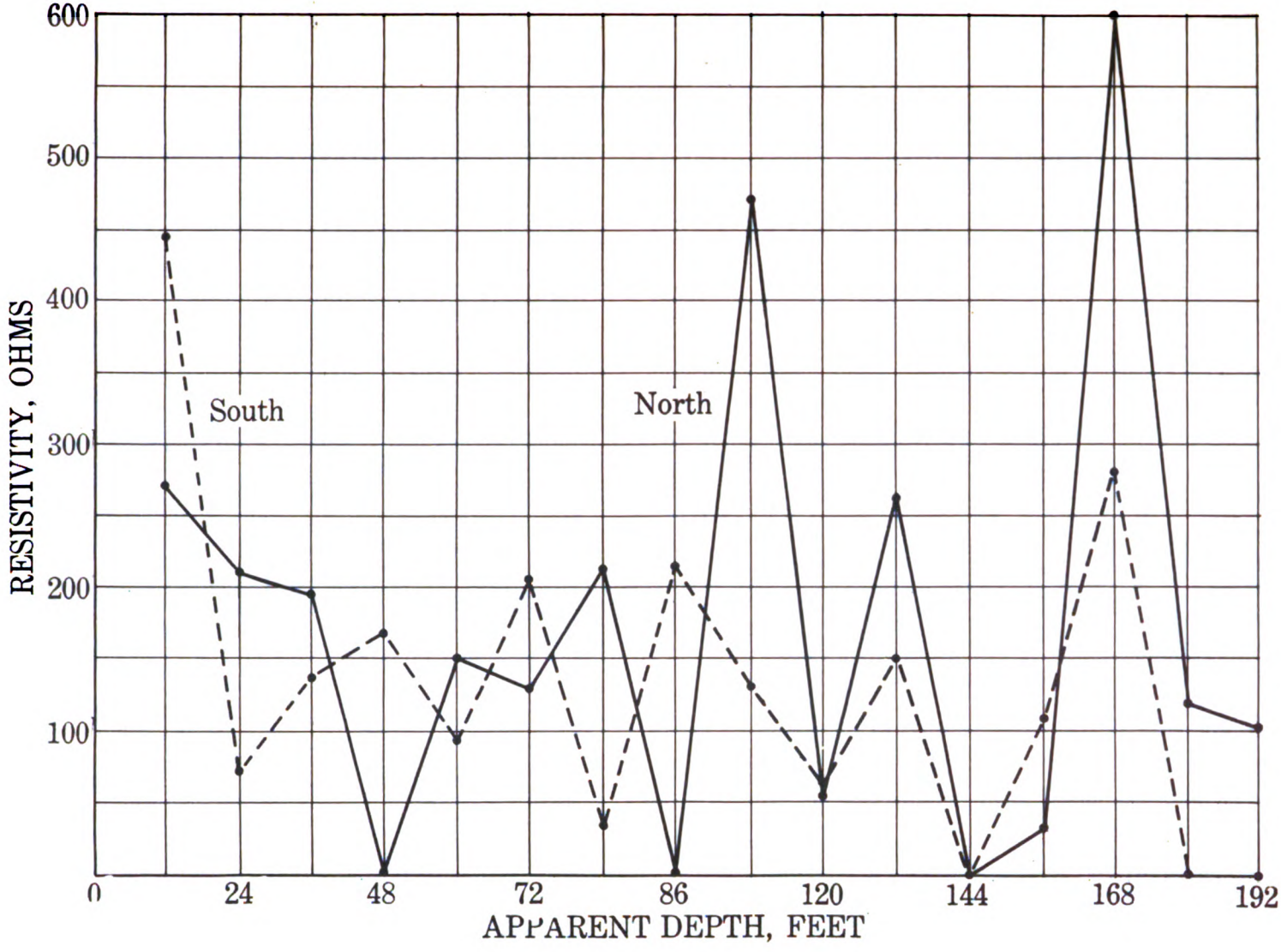

Figure 24.— Resistivity observations west of Lorenze's wells on line running north and south.

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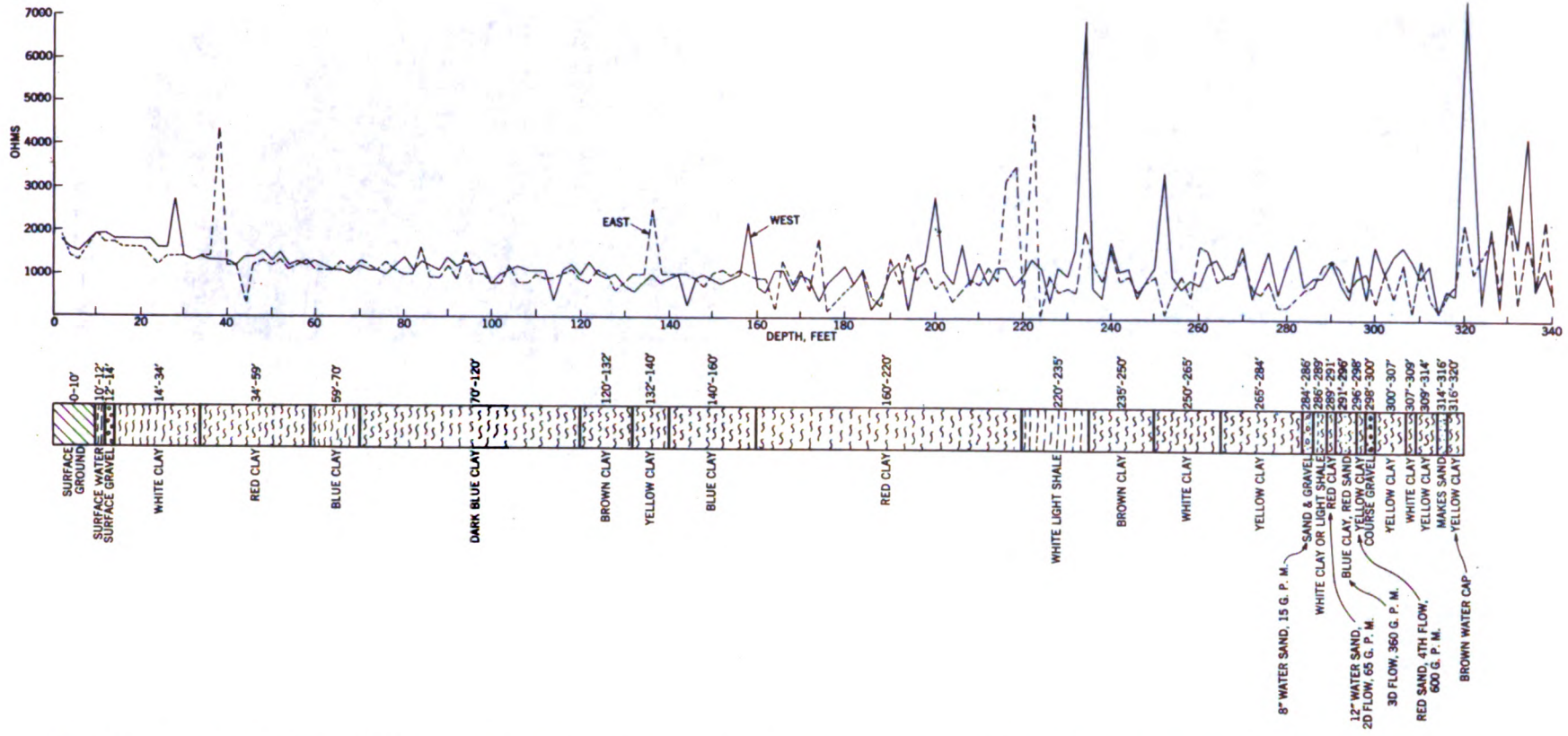

Figure 25.—Log of artesian well No. 4, 500 ft. west of Bartine's ranch house and detail survey of station E–4, 210 ft. east of artesian well No. 4, 260 ft. west of artesian well No. 2.

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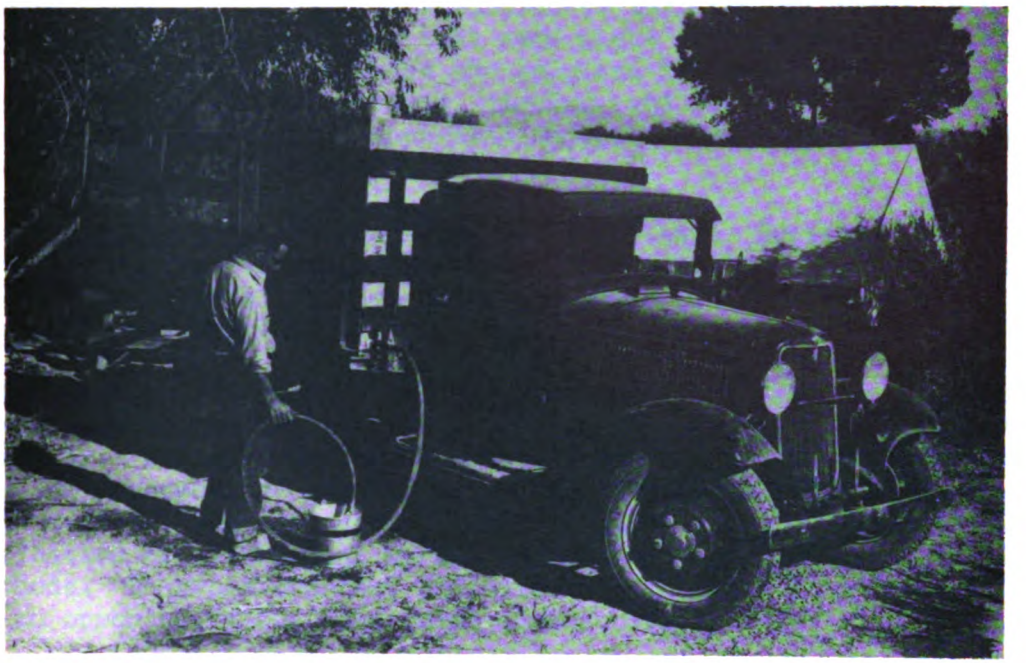

Figure 26.— 2-ton truck equipped for desert work.

Figure 27.— View of desert camp.

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though heavy, consequently requiring different transportation and field procedure. In the second place, it is best to condition or test the apparatus at a base or laboratory field station to insure that each piece of equipment is functioning properly. Transportation facilities are required for a considerable bulk, and much care must be exercised in boxing, packing, and storing. It is not generally to be expected that geophysical apparatus shipped by express will arrive at its destination in operating condition.

Many geologists work alone or with one assistant. Resistivity geophysical work generally requires three to five men per crew to make efficient headway in field exploration. There is, therefore, usually a greater burden in taking care of the personnel necessary for making observations.

In choosing men for geophysical work such as, for example, the search for gravel, good results can be obtained from graduates in the technical divisions of a university. Students having an aptitude for mining, with a good knowledge of geology and prospecting, coupled with general handiness are to be preferred. Even though most of them have had only a very elementary working knowledge of the field application of geophysical work, they can be taught quickly how to use the simple methods. To avoid monotony and stimulate interest it is best to give everybody an opportunity for performing each function.

At many places in the Southwest houses are more than 50 miles apart, even on well-traveled roads. Very commonly such places do not have hotel accommodations or the costs are too high for the men. It therefore becomes necessary to operate from a camp, which must, of course, be convenient to the locality in which observations are to be made.

A good camp should have not more than 12 men, including a cook and his helper. If more men are needed more camps should be provided. Too many men in a camp will load the camp equipment too heavily, and too few will make expenses too high per individual.

In the arrangement used, the cost of food and camp service per day was about 50 cents per man. Wages averaged $22.50 per week. The wages of the cook and his helper were carried by the State organization. Most of the men were accustomed to outdoor camp life, and necessary additional information was very rapidly imparted to those not so experienced. On the whole, everything moved very quickly with little or no lost motion.

A 2-ton truck, which carried a water tank having a capacity of 180 gallons, was used for field transportation (see fig. 26). A small, light car was also available for short trips and for emergency purposes. It was found that this arrangement was both effective and economical.

A FEW PRECAUTIONS TO BE EXERCISED IN OPERATING A CAMP IN THE DESERT.

In field work in the western deserts there may be some danger from rattlesnakes. There is usually more danger during August and September, because the snakes are shedding their skins at this time and do not give much warning before striking. High shoes or leggings should be worn as a reasonable precaution.

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Heavy boots and shoes and heavy woolen socks or stockings even in summer are advisable. If thin cotton socks are worn under the wool many blisters and much misery will be saved. In the field, a man's work depends so largely on the condition of his feet and this simple precaution is much more important than it may seem. A duffle bag instead of a suitcase is much to be preferred in packing and hauling. Sore lips, one of the curses of the desert, are usually quickly cured by cautious application of mercuric iodide or mercuric chloride soap used as a salve.

At night the temperature is low, and even in July several blankets are necessary for comfort on the desert. During the day the temperature is generally well over 100°F. In choosing a camp care should be taken to have, if possible, the shelter of a bank 6 to 8 feet high on the east, south, and west, and open to the north. Under such a condition a difference of as much as 10° to 15° temperature can be enjoyed even in midday. Such a camp is shown in figure 26.

It is possible to keep perishable foods, such as butter, orange juice, and eggs, in a "compound desert refrigerator." The reason for calling it compound is because the cooling is done in two stages. Ordinary desert canvas water bags are suspended over a crate covered with burlap. The water first evaporates on the water bags and reduces the temperature of the water dripping from the bags to the burlap on the crate, where further evaporation reduces the temperature of the already cold water. Butter so kept was generally too hard for easy spreading, and plenty of cool beverages were available for meals.

The field organization should be planned to permit each member to assume any field function and responsibility in turn. This is done to train as many leaders as quickly as possible and permit them, if necessary, to branch off with a crew of their own.

Plans for the work should be discussed thoroughly each evening and a critical review made of each day's work. This results in an almost frictionless organization in which every member wholeheartedly participates and cooperates. A photograph of such a group is shown in figure 27.

CONCLUSIONS

Geophysical surveys in Nevada can be made useful by helping to determine the underground water reserves. Enough water for moderate irrigation can be found in favorable districts. In many parts of the State a conservation program for outlining and charting such natural resources on a wider scale is practicable at present.

Sufficient differences exist in electrical conductivity between the gravel and clay beds to permit successful prospecting for water, especially at shallow depths. Where the water-bearing beds are as much as 350 feet deep, as in Bertine's artesian well, possible productive territory can be delineated and barren districts excluded.

Considerable increase in speed of field measurements as well as in interpretation is possible with the newer earth-resistivity measuring instruments. Much more experimental work relating to electrical conduction in the ground, especially concerning its character, is very much desired and will aid progress in this science.

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Very satisfactory results can be obtained from technical men inexperienced in geophysical work after a short intensive study of a specific problem.

Drought relief in this district would profit by an organization for analyzing important geophysical constants that bear directly upon water finding.

From a geophysical viewpoint, subterranean waters as a national asset have not been sufficiently understood or appreciated. They deserve much more careful study and research of this type than have been heretofore accorded them.

BIBLIOGRAPHY

A complete bibliography touching upon all electrical-resistivity methods would be too long to append to this paper. For a complete list of publications bearing upon this subject the reader is referred to the Geophysical Abstracts issued by the Bureau of Mines, which may be consulted in any good public library.

ACKNOWLEDGMENTS

This work was made possible through the aid of Congressman James G. Scrugham of Nevada and was carried out under the direction of the Federal Emergency Relief Administration by H. L. Hopkins and his assistants, J. Baker and P. A. Fellows, and under the administration of the United States Bureau of Mines.

In the field the author was greatly indebted to Dr. C. Creel and Frank P. Upman, Jr., directors of the F.E.R.A. of Nevada and also to their able staff.

A large amount of supplementary work was done with the assistance of Dr. Ellwood Mead, Commissioner of Reclamation, and his field organization.

To the hearty support of Prof. J. B. Fulton, Director of the Mackay School of Mines of the University of Nevada, much of the success of this work is due.

The writer also wishes hereby to express his appreciation and thanks to Wm. O. Vanderburg of the Mining Division, United States Bureau of Mines, stationed at Reno, Nev., for his many excellent suggestions and field cooperation.

To P. DeLongchamps, L. B. Grindell, P. L. Nichols, T. P. Overton, G. C. Schilling, and S. Wallace, assistants in the field from Nevada University, much credit is due for their loyalty and application. To A. Holt and W. Brand, who functioned as cook and provider, our sincerest thanks are due.

The execution of many of the proposals was under the direction of Neil McGill, engineer of the N.F.E.R.A., and the fine manner in which it was done testifies to his efficiency.

The writer also wishes to thank G. D. Keyser, Water Commissioner of Salt Lake City, Utah, for the assistance offered in the study of that district.

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APPENDIX I. - THE DIVINING ROD

The use of the divining rod for finding subterranean waters is of very ancient origin. At present such instruments still enjoy local favor even in geological departments of noted German universities. In the writer's opinion, most of such observations are motivated by autosuggestion, giving rise to self-delusion rather than willful deceit. A rather extended discussion of the divining rod by R. W. Raymond in the U.S. Geological Survey, Mineral Resources of the United States, 1882, has been freely drawn upon by the writer in the following:

From the Scriptures it is seen that Egyptian sorcerers carried rods, as did Moses and Aaron. The prophet Hosea (4:2), even in those early times, denounced their use. The prophet Ezekiel (21:26) informs us that the King of Babylon consulted rods and arrows to decide his course. From Herodotus we learn that the Scythians detected perjurers by the use of the rod. Students of the classics will remember the magic power of the rods of Minerva, Circe, and Mercury. That practical Roman, Cicero, a divining-rod operator himself, remarks that it would be impossible for two augurs to meet face to face without laughing. Marco Polo describes the use of the divining rod in the Orient. It was used by the ancients principally to determine moral conditions, guilt, future events, course of events, etc.

The alchemists first used the divining rod for mineral detection. It was here also a case of alloying superstition with science - their main forte. Philip Melancthon (1497-1516) explained its action to Luther as based on affinity, a word which at that time served to conceal rather than to elucidate.

The credence which it enjoyed was explained similarly to that of magnetic attraction, electrified amber, or other similar natural phenomena. This kind of explanation was especially necessary because the only alternative was demonic influence which would cost the operator his life. Even in those days the great Agricola advised miners to stick to pitting and trenching in preference to using the rod.

The practitioners at that time generally maintained that performances of the rod were genuine, and blended the virtues of the heathen manner of cutting the wand or certain heathen sorcery and astrology with the atonation of Christian baptism. According to Gaetzschmann the following christening formula was used: "In the name of the Father and the Son and of the Holy Ghost, I adjure thee, Augusta Carolina (name of the rod), that thou tell me, so pure and true as Mary the Virgin was, who bore our Lord Jesus Christ, how many fathoms is it from here to the ore?" The rod was then expected to dip once for each fathom of depth. However, Baron and Baroness Beausoleil did not fare so well. They were charged with sorcery, and their property valued at 100,000 crowns was seized. They were acquitted of the charge, but never regained their lost property.

Many pious church dignitaries discussed the rods, some Jesuits condemned them as diabolical, and any attempt to use them was censured by the church. Here, again, a revival of the moral possibilities of the rod developed with a decidedly practical slant. The rod was used to spot old landmarks in disputed boundaries, and the decision was accepted as final.

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In the nauseating case of Aymar of France in 1703, the divining rod was used to point out Protestants for massacre.

Chevreul first ascribed the movement of the rod to minute, unconscious muscular movements of the operator. Under this circumstance the writer has seen a practitioner twist the bark from a peach fork without knowing that he was doing it. Probably nobody has made a better summary of the phenomena than Chevreul, and the following is a brief condensation of the results of his investigations:

1. The consecrating ritual formalities are entirely irrelevant to its efficacy.

2. The rod itself is inert unless in the hands of the operator.

3. The favored form of the rod is the Y because it promotes involuntary muscular movement.

4. The minute involuntary muscular movements may be of subconscious origin or from a purely physical sensation.

5. The use of the rod for discovery of moral qualities will not be seriously defended by any one.

6. The agency of the demons may also be dismissed.

7. The application of the rod for finding minerals, coal, buried treasure, etc., is chimerical.

8. The transparent humbug of locating oil wells needs no comment.

9. There seems to be a small vestige of truth in the use of the rod for the discovery of springs where the rod acts as an indicator of minute muscular movements.

There is evidence of the practice of fraud by so-called geophysical prospectors who deceive individuals by simulating bona fide geophysical methods. They usually charge but a small fee and rely upon their royalty contract to reimburse them. After a sufficient number of mistrials, they may succeed, by the law of chance, in discovering productive territory.

Consultation with the Government departments, as well as recognized national societies, will save a great amount of disappointment and expense to those who contemplate using geophysical methods.

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